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Task-oriented Flight Control Systems

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PREFACE

This Lecture Series was recommended by the Guidance and Control Panel of AGARD and is implemenented under the Consultant and Exchange Programme.

Recent developments in data processing are establishing the viability of high-integrity, high-authority full-time electrical flight control systems, which in turn offer a range of new possibilities in the design of the control system and of the complete aircraft. The use of digital processors now allows the control system characteristics to be varied during or between flights to match particular operational needs. This concept of Task-Oriented Control Systems is the subject of Lecture Series No.89, which aims to present information on the benefits, problems, design and engineering aspects of these new developments, commencing with a state-of-the-art review of modern flight control theory and practice.

The contributions are based on the practical experience of the authors and their organisations in several nations. It is hoped that through the presentation of the papers and the subsequent discussions the Lecture Series participants will obtain sufficient background information to apply the technical principles to their particular requirements.

Geoffrey H.HUNT
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* Not available at time of printing.

INTRODUCTION AND OVERVIEW

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SUMMARY

The development of high-integrity programmable control systems opens up a range of possibilities for their introduction into future aircraft, including that of task-oriented controls. This introductory paper to Lecture Series No.89 gives an overview of some of the implications and problems, as well as the advantages, of applying these control systems to piloted aircraft.

1 INTRODUCTION

Flight control systems for aircraft are at the present time in a period of fairly rapid change, and in an introductory paper for this Lecture Series it is appropriate to identify the reasons for this change. They may be found in an assessment of the design of control systems as they have existed from the earliest days of flying until the very recent past. Such control systems are of course 'safety-of-flight' items which have the capability to destroy the aircraft if they fail in certain ways. Thus integrity and reliability have to be of similar values to that of other critical parts of the aircraft such as the airframe itself. This dictated the use of well proven mechanical systems. On the other hand the requirements for controllability, stability and precision of control were beyond the capability of purely mechanical systems and could generally be met only by the use of electrical and hydraulic systems using sensors and actuators, all of which have had integrity and reliability levels less than required, and less than available from mechanical systems. The solution to the dilemma was found in compromises of various forms. These frequently involved mixing together a mechanical system of high authority and an electrical system of limited authority, a concept which has been highly successful in a wide range of aircraft. The problem of hydraulic system integrity has generally been resolved by the adoption of varying degrees of redundancy.

Modern developments, particularly in the field of solid state electronics, are now bringing the integrity and reliability of electronic processors to the point at which by incorporating a reasonable degree of redundancy, acceptable system integrity values can be achieved. It then follows that the aircraft designers can obtain the full benefits of active control systems without being constrained by the problems of handling and stability in reversionary modes. Such benefits may include improved flying qualities, gust and load alleviation, relaxed static stability, stall and spin prevention and others which have previously not been obtainable or possibly available only in a limited form. An excellent review of these various possibilities is provided by the Proceedings of the 1974 AGARD Conference on "Impact of Active Control Technology on Airplane Design".

Although not essential for the implementation of full-time high authority active control, the use of digital processors brings a number of advantages. Foremost among these are the capability for extensive self-test both pre-flight and in flight, and the ability of parallel redundant computers to perform calculations without significant interlane differences. A further advantage is the relative ease with which they can be re-programmed, which offers the possibility of changing the control laws of the aircraft to suit its particular operational task.

Such a possibility is not strictly new, as autopilots have for many years been available with a number of modes which could be selected by the crew for use during appropriate phases of a flight. Similarly pilots have had available multi-mode displays. The use of multi-mode processors for inner-loop flight control to change the aircraft's pilot-in-the-loop handling characteristics is however relatively new and forms the theme of this Lecture Series.

2 ENGINEERING ASPECTS

Although it is possible to build a task-oriented flight control system based on a combination of a mechanical/hydraulic primary control system, together with a multi-mode electronic feedback system, it is now possible to design a fully electrical system with no mechanical reversion and the trend will be towards such a fully electrical or fly-by-wire system. Ideally such a system could be built with perfect integrity, but in practice the design has to be worked out on the basis of a very low statistical probability of system failure. To set a value on this probability is very difficult. For civil aircraft a catastrophic failure rate of the control system of no greater than 10^{-9} per hour seems to be generally accepted. For a military aircraft figures in the band of 10^{-5} to 10^{-7} per hour are generally quoted, largely based on the need to be no worse and possibly better than conventional systems.

Control systems are very largely based on electronic components, and the failure of electronic components is generally a statistical process. If a component is manufactured, tested and assembled into a working system then there is a finite quantifiable probability that it will fail within a given period of time. Much of course depends on the environmental conditions as well as the design, manufacture and testing of the component itself. The same applies to sensors and to some extent to actuators, although in these cases the numbers are rather different and there may be the additional complication of mechanical wear. But taking all the components together in a single-channel control system comprising a sensor, electronic processor and actuator, a failure rate in the region of 10^{-3} per hour may be regarded as reasonably good. This is well short of the required system integrity figures, even for a military aircraft. If account is also taken of the integrity of the electrical and hydraulic power supplies, it appears that the system needs to be designed to be operative after two component failures, implying either quadruplex or monitored triplex type of arrangement.

Having decided, for example, that a quadruplex arrangement of computers is to be used, there is still considerable scope for the arrangement of sensors, actuators and power supplies. The simplest in concept is to arrange for a completely quadruplex system which minimises interconnections between the four lanes, but may be unnecessarily expensive in hardware. The alternative is to have different degrees of redundancy in sensors, actuators and power supplies which reduces hardware but will lead to more interconnections, which are potential sources of single-point failures and therefore undesirable.

Calculations of overall system integrity are generally based on the temporal randomness of individual component failures. Any correlation between failures in redundant lanes will increase the probability of overall system failures. Such a correlation may be caused by an external disturbance, such as lightning, or by errors in the design of hardware or software in the lanes. Of these the most serious is probably lightning and electromagnetic interference, and the greatest care will be necessary in designing and proving the immunity of the system to lightning strike.

The use of redundancy to obtain integrity is only feasible if component reliability is good, and high reliability is also necessary to achieve acceptably high availability and low maintenance costs. It will also be very important to keep within reasonable limits the development costs of these systems, particularly the costs of integrity proving including the writing and testing of safe software. This area of system design, redundancy and integrity will continue to be at the heart of the development task for future active control systems. Other engineering aspects such as obtaining sufficiently fast and powerful actuators, use of improved types of sensor, use of fibre-optic data transmission and design of appropriate miniature sticks and pedals, may be expected to follow a steady evolutionary process.

3 THEORETICAL DESIGN

The theoretical design of aircraft flight control systems is based on a combination of two separate sets of theory. The first of these is the linearised theory of the equations of motion of the aeroplane, including the use of stability derivatives, which dates back to the early work of Lanchester, Bryan, Melville Jones and others. The second is the technique of servo analysis which was developed very rapidly during the 1940s, and in which the names of Nyquist, Bode, Evans and others are well known. The bringing together of these theories, together with the development of appropriate sensors, amplifiers and power actuators, led to the extensive application of flight control techniques in the last 2½ decades. In most respects this theoretical framework will continue to be adequate for the future, although it is now possible to identify problem areas which will need further theoretical development.

The first of these arises from the use of digital processors which sample and process data at intervals rather than continuously. This implies that use should be made of sampled data theory in the design of control systems rather than continuous data theory, particularly if the sampling periods used are of similar magnitude to the inverse of the bandwidth of the control loop. This will tend to be so in order to use the digital processors efficiently.

A second area which poses theoretical problems is that of structural interactions. The higher bandwidth control systems now being developed have bandwidths close to major structural mode frequencies of the aircraft. The simple solution to this problem is to attempt to minimise interaction between control system and structure by physical location of sensors and actuators away from sensitive areas of the structure. This may not lead to the optimum design, and it is desirable that structural modes should be included in the theoretical design of the control system, and that control system characteristics should be included in the structural design. The implementation of this concept requires that structural and control system theory should be brought together as a consistent whole.

A third area concerns the use of aircraft over a wide flight envelope including large angular motions relative to the normal attitude. The equations of motion then include non-linear terms due to both aerodynamic and inertial forces, and cannot be analytically handled by use of the well-established stability criteria. There appears to be no clear solution to this problem, and further extension of present techniques is likely, in which analytical study of linearised small-angle perturbations is combined with extensive computer simulation of large-angle non-linear equations.

Finally it should be mentioned that control systems can be designed which would minimise aircraft response to external gust disturbances. To achieve good performance in this respect it is necessary to have accurate models of gusts and also a clear understanding and definition of the response parameter to be minimised.

4 HUMAN FACTORS

Modern flight control systems, including multimode or task-oriented controls, are designed and developed using complex, sophisticated and precise theoretical techniques. It is one of the ironies of this field of science that for piloted flight the control system is interfaced with a human operator who cannot be modelled in any precise form and who is highly adaptable and variable in his behaviour. It would be unwise to predict any significant change in this situation. The consequence is that the design criteria for the control system can only be specified in a relatively inexact form. Military specifications for the flying qualities of piloted aircraft, for example, lay down boundaries for frequency and damping requirements which are quite widely separated. A further problem for the control system designer is that these criteria are usually specified in terms of a familiar second order system response, whereas modern control systems are typically of higher order.

For the future task-oriented control system there are further complications. First is the additional freedom in design of control stick and rudder arising from the use of a non-mechanical control system. A miniature control stick now becomes possible and has real advantages in cockpit layout, but appropriate design criteria for such sticks have not yet been developed. Second is the possible use of additional degrees of freedom provided by direct lift and direct sideforce motivators. The pilot cannot be expected to control an additional two degrees of freedom, so some blending of his controls to reduce the task to manageable proportions is clearly necessary. A third complication is that it is not yet clear how much

dissimilarity between control characteristics will be acceptable to the pilot, and how to achieve reasonable transition between these modes. A fourth is that if one mode is being designed specifically to be optimum for one task, e.g. weapon aiming, then a handling quality criterion appropriate to that task must be defined.

It is clear that there are many problems associated with the pilot handling of a task-oriented control system which will require study before the maximum advantage can be derived from such systems. Because of the difficulty of adequately modelling the pilot's behaviour, these studies can only be carried out by simulator trials or flight trials. Fortunately, due to the development of powerful digital computers it is possible to carry out such trials much more readily than hitherto. Because of the largely empirical and evolutionary nature of the trials, progress in this area is likely to be relatively slow and will possibly be a limiting factor on the whole development of task-oriented control systems.

5 AIRCRAFT DESIGN IMPLICATIONS

Full-time active control systems offer the possibility of considerably improved aircraft performance, but to achieve that potential the aircraft and its control system must be designed as an integrated whole. The need for this has already been mentioned in connection with the structural design and its interaction with high-bandwidth control loops, but in other areas also the control system interacts closely with the aircraft design. As an example, the use of full-time stability augmentation in the pitch axis will change the normal ground rules for the structural and aerodynamic design associated with that axis. The use of limiters in the control system to enable the pilot to fly closer to aerodynamic and structural boundaries may also require that existing structural design criteria be modified.

Task-oriented control systems which are designed to give accurate control for weapon-aiming tasks will incorporate additional degrees of freedom which in turn will require additional control surfaces. The combination of these with the relaxation of existing aerodynamic stability criteria may well produce new aircraft of unfamiliar shape. In the cockpit, also, the removal of the conventional centre stick and its replacement by a miniature stick will allow the aircraft designer a degree of design freedom which may result in significantly changed cockpit designs.

6 WEAPON IMPLICATIONS

The pilot of a weapon-carrying aircraft controls the aircraft's attitude, velocity and position such that the weapon after release will strike a target. Considered as a whole, the control task incorporates the dynamic behaviour of the aircraft and of the weapon, the aircraft being used to set up the initial conditions for the subsequent flight of the weapon. It would appear that to achieve optimum overall system performance, the aircraft's control system should be designed to match the requirements set by the weapon dynamics. With the additional degrees of freedom becoming available, and with re-programmable processors incorporated in task-oriented control systems, such an optimisation is theoretically possible. Detailed studies, including man-in-the-loop trials, will be necessary in order to establish the sensitivity of success rate as a function of variations in control law.

7 CONCLUSION

The development of high-integrity programmable control systems opens up a wide range of possibilities for their implementation. At this time there remain many problems to be solved, both in the detailed design and engineering of the control systems, and in the wider aspects of their application to total aircraft/weapon systems. Of particular significance are the changes that may be necessary to existing structural and aerodynamic design practice and the establishment of adequate handling criteria to take account of the human factors aspects. Because of the wide implications of introducing task-oriented controls, and their key position in the safety-of-flight of the aircraft, progress in this field will necessarily be evolutionary rather than revolutionary.

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ENGINEERING OF CONTROL SYSTEMS AND IMPLICATIONS ON CONTROL LAW DESIGN

by

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SUMMARY

Future combat aircraft employing task oriented control will require full authority and, in most cases, full time digital control. This paper reviews the state-of-the-art of multiplexed digital FCS against a background of the integrity requirements and the means of achieving integrity. As an introduction, the need for variable and changeable control is discussed; and the potential of pilot selectable task oriented control is examined. Limitations to the performance of aircraft plus its FCS result from limitations in FCS components and subsystems; and the control policies that can be applied with confidence.

1. INTRODUCTION

The development of Flight Control Systems (FCS) has been evolving over the past several decades and continues to evolve at an accelerating rate in order to meet anticipated future requirements. As experience and confidence has grown, greater reliance and greater authority has been placed in the use of electronics in such systems. This confidence has increased rapidly in the last few years as a result of the work[1,2] in the US and, to a lesser extent, in Europe in establishing the practicalities of using full time as well as full authority 'fly-by-wire' control.

It is now recognised that the performance of future aircraft - or rather future aircraft plus future FCS - will be achieved from the integral design of three, previously separate, factors: the airframe and its control surfaces; the control laws shaping the pilot's input and motion sensor feedback to the control surfaces: and the FCS with its electromechanical, electronic and electrohydraulic subsystems. These three aspects of design need to be considered simultaneously in order to maximise performance of the aircraft and its integrated FCS.

As part of the AGARD Lecture Series on "Task Oriented Control", this paper aims to review in general terms the properties and characteristics of the next generation of FCS, to discuss outstanding problems and to suggest future trends. In reviewing the state-of-the-art of FCS, it is desirable to discuss how the properties of the system interact with control law design which, in turn, interacts with the performance of the aircraft plus system. Certain properties of the FCS limit and constrain whereas other characteristics offer concepts which could lead to improved performance.

One concept of considerable potential follows from the relative ease with which the next generation of FCS can be reprogrammed since, for systems reasons alone, digital processors will be used. If the FCS is designed to permit such changes, then changes could be made either to maintain flying qualities as the aircraft characteristics vary between or during flights: or, through a pilot operated task mode switch, to change the flying qualities during flight so as to optimise the aircraft plus system for different high performance flight tasks. The use of multiple control surfaces and motion sensors, selected with such control in mind, increases the range of dynamic characteristics that would be variable and selectable in such a system. The potential benefits of this task oriented control concept need considerable study. In parallel, it is important that system developments proceed so as to ensure rapid application to future aircraft.

Practical limitations to the speed of control are the main factors which constrain performance. Since all inputs to the FCS computers are imperfect, filtering is required to attenuate noise, eliminate static errors and reduce undesirable modes of motion picked up by the sensors. Such filtering, together with delays in the computing, introduce lags which combine to constrain the maximum achievable frequency of the control loop. Studies have begun in the UK into more advanced control laws which would vary the control rapidly with conditions so as to obtain rapid response when and only when such control is needed.

The outstanding system problem relates to integrity and how to demonstrate confidence that the desired integrity will be achieved. Multiplexing of subsystems such as sensors, computers, actuators, and power supplies is required in order for the aircraft to remain flyable after one or more failures. Systems in many in-service aircraft, civil and military, employ full authority redundant control with reversion to mechanical flying controls when the FCS fails. Such reversionary control complicates the overall control system and limits the performance potential of the aircraft plus system. It is generally accepted that there is sufficient experience and confidence, at the present time, to design a combat aircraft without mechanical reversion - witness the successful F 16 - but that, since the integrity requirements are more severe, application to civil transport aircraft requires more evidence that the integrity will be achieved and this can come from experience alone. This paper is concerned primarily with full time FCS for combat aircraft although much of it has relevance to future FCS for all types of aircraft whether the FCS is full time or not.

The use of multiplex lanes to provide appropriate redundancy ensures that the system remains operational following FCS failures for the great majority of possible types of failures. Because these multiplexed lanes are not totally independent, there are possible causes of failures that may effect more than one lane and it is essential to seek out such failure cases and find appropriate means to eliminate or make sufficiently remote the chance of such failures. In the UK there has been a research and development programme into multiplexed FCS since 1958, when designs for the first multiplexed autoland systems were begun. In recent years attention has been turned to full time digital systems. The discussion of system failures given in this paper is based on this UK work.

An important part of the FCS is the system management and the interface with the pilot. The use of full time FCS leads to the possibility of improved designs of inceptor (stick, pedals, throttle lever etc.) with a decrease in weight and improved cockpit space as well as yielding more precise control. A pilot's FCS status display, an automatic pre-flight check facility and in-flight monitoring of the failure-survival status of the FCS are required. It is also essential to design the system to allow rapid location of failed components to line-replacement-unit (LRU) level.

2. THE NEED FOR VARIABLE AND CHANGEABLE CONTROL

In the simplest terms, the control loops of the FCS perform two types of function, Fig.1. The 'auto-loop', the product of Control (1) and the aircraft, can be viewed as controlling the aircraft's response to external disturbances. Theoretically, the aircraft can be designed without regard to stability, ride or any other dynamic requirement since these requirements can be met by appropriate choice of Control (1), actuating system, control surfaces and motion sensors. In theory, also, given the characteristics of the auto-loop, Control (2) can be chosen to 'shape' the pilot's input so as to attain the desired aircraft's response to pilot's demand.

In practice, a number of factors will limit the extent to which this process can be taken, one being the properties of the FCS itself; imperfections of sensors, delays and lags in the control, rate limits of the actuating system, etc. As the FCS technology develops in order to meet antitipated requirements such limitations will decrease.

A second limiting factor is our ability, at the present time, to use only linear control theory in the design of the control laws; the aircraft model, control loops and FCS subsystems are usually assumed to be linear and stationary in the design. Although the control is varied in many in-service autopilots and autostabilisers, a piecemeal rather than an integrated design has been used. This has been due partly to the need to minimise the amount of variations so as to reduce the complexity of analogue systems. In addition to discontinuous changes to the control either between flights or during a flight, it is desirable to examine the potential of varying the control continuously as a more complex function of aircraft and FCS state than previously. With the advent of digital control, this potential should be realised in the next generation of combat aircraft.

For simplicity, the auto-loop was drawn in Fig.1 as a single loop. In practice, there are many loops within the auto-loop, each one associated with each motivator, a term used for any device used to change the aircraft's motion. Control (1) in each loop and cross loops between these can be selected and varied to improve and change performance with respect to external disturbances. Similarly, the pilot loop is multi-loop, each being associated with each degree of freedom of the pilot's inceptors (stick, pedals, throttle lever etc.). Control (2) in each of these pilot's loops and between pilot and auto-loops can be selected and varied to improve aircraft's response to pilot's demand.

2.1 Changes during aircraft and system development

During development there is considerable uncertainty in the aircraft characteristics up to and including test flying. A re-programmable system would alleviate this problem in many cases.

Related to this is the possibility that difficulties in flying qualities will be experienced during development flying. It is generally accepted that current criteria for flying qualities are a good basis but, as yet, inadequate for aircraft with advanced FCS.

2.2 Changes during service

A more flexible in-service aircraft could result if the system could be re-programmed (between flights) to compensate for changes in aircraft characteristics due to extra fuel, different stores or their location. Such aircraft changes would be known so that the control changes would be defined and fully flight cleared.

It is possible that the control will be tailored to the particular mission, e.g. type of weapon carried. Changes in mission during the aircraft's service could lead to the need to change the control.

It is likely that flying qualities criteria will evolve gradually as experience is gained and as research on this subject progresses. Changes in the control could be made to implement agreed changes in flying qualities.

These are all changes to the control between flights or at greater intervals of time.

2.3 Variations of control with aircraft state

In-service systems have, of course, used controls which are varied to account partially for variations in aircraft characteristics across the flight envelope. These have been restricted, in the main, to relatively slow varying aircraft states such as airspeed, Mach number and height. In effect, both types of control loops (1) and (2) have been varied although, in many designs, a clear distinction has not been made between them.

As the aircraft manoeuvres over its flight envelope, approaches its flight boundary or changes its configuration, Control (1) can be varied to maintain good dynamic characteristics of the auto-loop and Control (2) can be varied to maintain good but not necessarily constant characteristics in response to pilot input. The control is varied as a scheduled function of available aircraft states estimated from motion sensors (speed, height, incidence, sideslip, etc.) and from transducers defining aircraft configuration (flap setting, airbrakes, undercarriage, etc.) or sudden changes in flight phase (e.g. touchdown). In particular, control is transferred automatically between control surfaces as their effectiveness changes with aircraft state.

For a given aircraft plus system, there are boundaries beyond which control will be unobtainable. These boundaries may be wider with an advanced FCS, and more sharply defined, than in conventional aircraft. Stall departure, spin prevention, spin recovery, load or g limiting are examples associated with flight boundaries defined by aircraft state. Another example follows from the fact that the acceptable flight boundary with the FCS fully operational is likely to be greater than that when part of the FCS has failed. Automatic transfer to the more limited flight boundary following such failures may be desirable.

All these variations in control are scheduled with respect to sensors measuring the state of the aircraft or FCS. The system is pre-programmed and relies on accurate modelling of the aircraft, its motivators, sensors and other parts of the FCS. The more complex these schedules, the more difficult the modelling and the design problem. Allowance must be made for errors and tolerances in defining states which leads to some reduction in the boundary imposed. The question arises as to whether the system cannot be designed to self-adapt to automatically correct for aircraft variations so as to remove the need for accurate modelling and possibly decrease the number of sensors and transducers required. This requires Control (1) to be varied so as to maximise a performance criterion chosen to embody all significant aspects of performance. This approach has not been successful as yet; it is difficult, perhaps impossible in general, to ensure satisfactory damping of the auto-loop from available measures of aircraft state alone. In control terms, it is difficult to ensure satisfactory pole positions as the control is varied.

2.4 Variations with amplitude and rate of control

With linear control, the control signal applied to each motivator is proportional to the error signal between demand and the appropriate combination of measured aircraft states. Studies in the UK have begun on possible control policies which remove this unnecessary limitation. In effect, the control is varied through values that are pre-programmed to be acceptable in terms of damping. Some simple examples are given below to illustrate the approach and the potential performance benefits.

A conflict occurs in selecting linear control for aircraft's longitudinal response to pilot's stick demand, elevator only. Extreme cases are shown in Fig.2. The first (a) yields rapid acceleration response but the resulting pitch rate overshoot leads to a 'nodding' effect in pitch attitude during tracking of a target[3]. The second (b) gives a dead beat pitch rate response, but gives a sluggish normal acceleration response unacceptable for rapid manoeuvring. In the non-linear scheme, Control (2) is varied with amplitude of pilot's stick demand (predicted) so as to achieve (b) for small amplitudes and (a) for large amplitudes and a blend of (a) and (b) for intermediate amplitudes.

The second example is associated with the conflict between, on the one hand, the use of filters in the auto-loop to attenuate the effects of sensor noise with a consequential decrease in speed of response of the auto-loop and, on the other hand, the need to increase the speed of response particularly when the rate of change of error signal is large. For example, the pitch rate response to pilot's demand, (b) in Fig.2, can be made more rapid without overshoot only if the frequency of the dominant mode of the auto-loop is increased above that acceptable, for fixed control over a long period, from relative damping and sensor noise considerations. With the variable control concept, the control is varied to increase the frequency, whilst maintaining relative damping, only when the rate of change of demand is large, resulting in the more rapid response, (c) in Fig.2.

Another example of future variable control arises out of the difficulties and compromises in scheduling Control (2) to obtain the desired variation in aircraft's response to pilot's demand across the flight envelope. The scheduling compensates, ideally, for variations in the auto-loop of both poles and zeros. Although considerable difficulties have been experienced with self-adaptive systems which aim to adjust pole positions, i.e. frequency and relative damping of the auto-loop modes, little attention has been given to the possibilities and advantages of self-adaptation of Control (2) to compensate automatically for variations in zero positions, the feed-forward terms between pilot demand and the state variable of interest.

These variable control concepts have been discussed with respect to aircraft's response to pilot demand. They are appropriate also, with perhaps more potential, to the auto-loop in reducing the effects of external disturbances such as wind; and, in particular, to an advanced autopilot.

2.5 Task oriented control

Since their introduction, autopilots have been designed with pilot selectable modes and these modes have been chosen for specific tasks: the task oriented control concept is not, therefore, a new one. Application to an integrated FCS for combat aircraft increases the complexity of the system from the pilot's point of view and could lead to an increase in pilot's workload and pilot error. There will be an advantage with pilot's selectable modes only if there is significant improvement in performing a specific high performance flight task compared with that of a system fully exploiting variations with measured aircraft and FCS states, as outlined in sections 2.1 to 2.4 above. With regard to the design of future autopilots, the reverse trend may occur; a decrease in the extent of selectable modes by appropriate choice of automatic variable control with aircraft state.

However, situations do arise when, for identical aircraft and FCS states, different control could yield significant performance improvements. A particularly important case is low level, high speed flight. Different Controls (1) and (2) could be desirable for three cases, Table 1; prolonged flight at low level, weapon aiming during ground attack and combat.

2.6 Summary

The several different variable control concepts discussed above are summarised in Table 2, where emphasis is placed on the problems in control law design. Closely related are the problems of assessing anticipated performance improvements not only in flying qualities but also in the use of the system.

Flight simulation alone will not lead to correct assessment and any ground studies must be supported where possible by experimental flight tests.

In effect, the coupling between aircraft and system performance, control design and research, and the development of the FCS is such as to produce a multi-loop control problem of a very complex kind, Fig.3.

3 INTEGRITY REQUIREMENTS

The subsystems of an integrated FCS are outlined in Fig.4. Included are electrical and hydraulic power supplies, the pilot's inceptor (stick, pedals, etc.) and FCS displays for pilot and maintenance personnel. An important consideration is the connecting cables between different subsystems which are positioned at all parts of the aircraft. Factors of importance are weight, maintainability, availability, and cost but the overriding problem is that of integrity.

It is generally accepted that the introduction of a more advanced FCS should not increase the rate of aircraft loss. This assumption may be questioned since the improved performance could be offset against some increase in loss rate. Recent analyses have confirmed that, for peace-time operations, combat aircraft loss rate is about 10^{-5} per flight hour of which 50% could be attributed to the FCS or its use (misuse): civil operations are at least one order better. This target must be divided in some way between different failure cases. The division shown in Fig.5 is arbitrary but useful in establishing required levels of redundancy.

Failures are divided first into FCS defects which, in an ideal system would be absorbed by the multiplexed system, and 'performance' failures attributable to inadequacies in flying qualities through the selected control laws combined with 'pilot errors'. In practice, not all FCS defects will be absorbed by the multiplexed system although as experience is gained the likelihood of such defects decreases. Allowance is made in the division in Fig.5 for failures not absorbed or absorbed in an incorrect fashion in the multiplexed system.

All parts of the FCS need not possess the highest integrity. Functionally, two classes can be defined, Class (A) being that required to keep the aircraft flying within a restricted envelope so that it can return to base; and Class (B) that combines with (A) to provide high performance over the complete flight envelope and for all flight tasks. As with current in-service systems with reversionary mechanical flying controls, reversion to Class (A) should not occur often, less than (say) 10^{-3} per flight hour, and loss of aircraft during and following reversion must not be frequent. Allowance is made in the division of the target failure rates, Fig.5, for the product of the frequency of reversion and the risk of aircraft loss during and after reversion.

The loss of aircraft due to those FCS defects which should be absorbed by the Class (A) redundant system is, therefore, a fraction of the target overall loss rate. As shown by the 'three failure' case in Fig.5, it approaches 10^{-7} per flight hour. Against this is set the failure rate of a single lane, estimated at about 2×10^{-3} per flight hour for the next generation of FCS equipment. A 1-failure survival system does not meet the target, yielding an estimated aircraft loss rate of more than $(2 \times 10^{-3})^2$ per flight hour due to Class (A) FCS defects alone. Therefore, a 2-failure survival system is required for Class (A), e.g. a quadruplex system relying on majority voting at the actuator output and, perhaps, elsewhere in the system; or a fully monitored triplex system.

For large authority Class (B) functions, a single defect survival system is necessary in order for the aircraft to be returned safely to a flight condition at which the aircraft would survive a second Class (B) failure. The return to the safe flight condition should be rapid and preferably automatic within the Class (A) control with some means of pilot override. An important difference between the two classes of control is the defect detection philosophy; it is suggested that for Class (B), the principle to apply is 'if in doubt, switch out' even at the expense of an increase in 'false failure' cases. In contrast, for (A) the full time part of the system, 'if in doubt, leave in' particularly after a second failure which is critical to the loss of aircraft. A change in failure detectiion algorithms after first and second failures may be advantageous for Class (A) control.

From an integrity point of view, physical separation of Class (A) from (B) would appear preferable, using dissimilar technology and keeping Class (A) as simple as possible. This approach could be essential for civil applications. The concepts discussed in section 2 lead to more complex and variable functions, mainly Class (B), which supports the idea of physical separation. However, the resultant increase in weight and engineering complexity is unlikely to be acceptable in a combat aircraft. Common computing, at least, is preferred and this should be digital to yield the desired flexibility.

Further divisions could be made, e.g. division of the Class (A) failures between the FCS subsystems. However, the exceedingly small numbers are somewhat meaningless except in selecting the degree of redundancy required. A different approach has been sought and may evolve along the following lines.

The overall target of 0.5×10^{-5} per flight hour is an average over a large number of flights, not the risk on a particular flight or under specific conditions, of flight or failure. There are cases, potential and actual, where a single failure would, in itself, lead to aircraft loss or very high risk of aircraft loss: such cases need very careful consideration. All other failures lead to an increase in risk of aircraft loss following failure. In the approach suggested, each failure case and combinations of 2-failure cases are considered separately in order to assess whether the frequency of occurrence of the failure and the risk after the failure are acceptable. It would be advantageous to define a maximum frequency of occurrence and a maximum risk of loss following a failure such that the product is less than some fraction of the overall target. The sum of these products over all failure cases should be less than the overall target. As a tentative suggestion, the maximum allowable frequency of experiencing a particular failure is set at 5×10^{-4} per flight hour; and the maximum risk of aircraft loss during and following failure is set at 10^{-4} per flight hour. The product for each failure case is set at 5×10^{-8} per flight hour. This implies 100 failure cases, the right order of magnitude. Any failure situation which could

occur at a frequency greater than 5×10^{-8} per flight hour must be survived, i.e. there must be an alternative course of action. The risk in taking this course of action, no matter how infrequent the failure, must be less than 10^{-4} per flight hour.

One of the main advantages of this suggested approach (and it has been suggested before[4]) is its use in failure effects and analysis, the means whereby the certificating authority can see that all possible precautions have been taken and that no foreseeable failures have been disregarded.

4 DESCRIPTION OF MULTIPLEXED DIGITAL FCS AND ITS SUBSYSTEMS

The 2-failure survival requirement for Class (A) full time control is met by a fourfold redundant system, Fig.6, (or by a fully monitored triplex system), in which lane failures are detected, isolated and flagged by a combination of failure absorption and monitoring using four (or three) digital processors. Each computer performs control law calculations for all axes of control, both Class (A) and (B) functions, so that there are as many separate outputs from each computer as motivators (excluded from Fig.6 for clarity).

Within this broad structure, there are many alternatives, some of which are discussed in this section. Attention is given to the conflicting interests of integrity on the one hand and the size, weight, cost and engineering complexity on the other. Factors affecting the achievement of integrity, problems of failure effects and the concept of visibility are discussed in greater detail in the next section. The two sections together cover 'hardware' and 'software' aspects of the FCS.

4.1 Actuation and hydraulic supplies

At the present time, multiplex actuators are electrohydraulic and will fail if the aircraft's hydraulic supply fails. Combat aircraft normally have two supplies, the failure rate of one being about 10^{-4} per flight hour. The aircraft loss rate due to FCS failures through total hydraulic failure is, therefore, about 2×10^{-8} per flight hour, which is within the suggested target.

The requirement for Class (A) full time control leads to the need for the actuator to survive two lane failures; or one hydraulic failure followed by one lane failure. A recent study in the UK outlined more than 100 possible arrangements. The ones described here employ force-summed averaging at the multiplexed output. In each case, the common mechanical output is fed-back, via multiplex transducers, to the four digital computers functioning as voter monitors which act to reduce inter-lane disparities within the actuators. This arrangement eliminates the need for four separate voter monitors, the more conventional approach.

The most straightforward and, perhaps, the most attractive is the duo-triplex, failure absorption system, Fig.7(a). Each supply is fed to each triplex half so that the supplies are kept separate. There is no need for devices within each actuator lane to monitor or isolate faulty lanes since such failures are absorbed by the actuator. Development of this subsystem in the UK has shown that, because of the absence of monitoring and isolation devices, its size and weight is comparable with the other two arrangements which use fewer lanes. The disadvantage is the need for six voter monitors, with connecting cables, only four of which are supplied by the digital computers.

In the duo-duplex actuator (b), each supply is again fed to separate halves of the actuator. An isolation device is necessary to remove failed lanes after failure detection and the inclusion of this device increases the size, weight, cost and engineering complexity of each lane compared with the failure absorption duo-triplex actuator (a). Following either one hydraulic supply or two lane failures, a further lane failure would be detected by an output difference and then, and only then, the monitor is used to determine which lane to reject and isolate. A monitor with a very high integrity is not required, and the thresholds are the relaxed ones for third failures, thus avoiding false failure problems associated with inaccurate modelling of the actuator, for both fully operational and failed states of the actuator: which is needed for a very high integrity monitor.

The main problems with the use of shuttles, (c), are, firstly, how to design the switch to ensure no discontinuity in operation during failure detection, testing and isolation; and, secondly, how to test to the required level of confidence that a good supply is not switched into a leaky actuator lane, thus experiencing loss of two supplies for one lane failure. In the UK, there has been insufficient experience to apply this technique to a very high integrity FCS. The dubious inclusion of some form of test device to each actuator lane so as to ensure the lane is not leaking increases the size, weight, cost and complexity of each actuator lane in comparison with the duo-duplex actuator (b).

Use of hydraulic switching or the addition of a third hydraulic supply and use of a high integrity monitor reduces the 2-failure survival actuator to a three lane device which interfaces best with a monitored triplex computer system. The overall size and weight of the system appears to be less than the other three discussed above but the increased complexity of the actuator, the need for a high integrity monitor, and the increase in the number of connecting cables must be taken into account.

4.2 Flight control computers (FCC)

Since 1971, there has been an R and D programme in the UK on multiplexed digital control which has led to several successful developments: Concorde air-intake, Tornado autopilot, YC 14 AFCS and a Sea-King helicopter auto-stabiliser. These systems use different Central Processor Units (CPU) which were designed specifically for the purpose.

As shown in Fig.8, the FCC is hybrid. Analogue inputs from motion sensors, inceptor pick-offs, actuator outputs etc. are passed first through analogue filters so as to eliminate aliasing, i.e. conversion of high to low frequency signals. After processing, the signal is passed again through analogue filters so as to eliminate undesirable effects of quantisation noise.

Motion sensor and other analogue inputs, therefore, experience delays and lags due to the input analogue filter, processing in the CPU, the sample and hold, and the output analogue filter. The most severe requirement results from the use of the FCCs as actuator voter monitors. Typically, the sample and hold must be less than 10ms and the time delay in the CPU must be no greater than 10ms. The requirements for other inputs are less severe for conventional control policies but could become as significant if some of the variable control concepts discussed in Section 2 are applied.

This severe time delay requirement is important in selecting the processor. For example, there is a choice between direct or indirect data access, Fig.9. For the first (a), analogue data is fetched from the multiplexer output under control of and at the time demanded by the CPU program. Similarly, the processed data is output without delay to the sample and hold, overall processing delay being about 1ms.

For the indirect data access (b), all input data is stored in a memory separate from the CPU which fetches this data once per unit program time or 'frame'. Typically, this frame is 5ms long. Similarly, the processed data is output via the data memory to the sample and hold once per frame. There is a delay of just less than one frame between the input to the multiplexer and the output to the sample and hold for signals not transmitted between lanes. Data from other lanes is transmitted in digital coded form once per frame. This data is used by the CPUs in the next frame in order to ensure each CPU uses the same data. The delay increases to just less than two frames for multiplex operation.

The internal data path structure in a typical CPU is shown in Fig.10. Instructions are interpreted by a microprogram held in separate programmable read-only memories (PROM). The PROM packages in the program store can be arranged in rows each representing (say) 1024 words of program, the total program being (say) 16K. In some processors, the program can be modularised such that each module uses a fraction (about half) of each row in the start program. When changes are made to the program, the module may expand but should remain within its PROM row, thus safeguarding all other parts of the program. A further safeguard is the separation of Class (A) and (B) functions such that any suspected program fault (e.g. program stuck in a loop) results in reversion to Class (A) operation.

Specific precautions are taken to saturate the accumulator A or its extension E, Fig.10, on overflow, e.g. when adding two numbers whose sum is greater than the capacity of the accumulator the result is the maximum positive or negative number. This saturation can be performed by a separate subroutine at the expense of uncertainties in instruction time or by a special hardware device.

For FCCs using DMA, the program and data stores are physically separate and each has a separate series of logical addresses. The CPU has two address registers to accommodate this. Typically, the data store in the DMA contains 2K words of read/write memory using bipolar random access memories (RAM) and 1K of constant data using PROMS. These PROMS and those in the microprogram memory are power switched in rows to reduce power dissipation.

With low power Schottky transistor-transistor logic (TTL), the microstep clock rate is typically 1.4MHz yielding average instruction times of 2.4μs. Next generation technology would allow this to be speeded up, if this is required.

4.3 Sensors and transducers

Inputs that may be used in an integrated FCS are given in Table 3. Not all need be 2-failure survival and in some cases, e.g. airstream sensors, it is difficult to fit quadruplex sensors on the aircraft, and they may be vulnerable to external effects such as bird strikes. The division into Class (A) and (B) must recognise this and suitable control laws chosen even at the expense of aircraft plus system performance. The use of estimators and other modelling techniques may reduce the number of sensors or improve failure survival capability with fewer sensors in future systems.

The multiplicity of sensors and transducers, together with their signal and power lines, increases the size, weight and complexity of the IFCS. The trade-off between the need to reduce these and the desire to achieve improved performance is difficult; each aircraft case is different.

4.4 FCS status displays

The pilot requires to know only the status of the aircraft plus system in terms of its flyability. For Class (A), he requires to know which of three states the system is in; fully operational 2-failure survival (no warning), degraded to 1-failure survival (amber warning), or the remote situation that the next failure could lead to loss of aircraft (red warning). These three states must be displayed unambiguously; and with an integrity approaching that of the system.

For Class (B) control, the pilot needs to know which flying qualities have been degraded by the loss of sensors, transducers and other subsystems rather than the sources of the degradation, e.g. loss of side-slip sensor. For pilot selectable task oriented control, the pilot's display must include high integrity switches with suitable annotation related to the flight task and warning (e.g. amber light) when the additional performance is unavailable. For other Class (B) control functions, similar (unswitched) data is preferred. Such Class (B) failure warnings are required whether the additional control is in use or not. If in use, additional cues are needed; e.g. by stick feel change together with automatic return to safe conditions if the pilot does not override the auto-loop control; by additional audio warnings if he decides to override it. It is arguable whether the pilot should be allowed to switch off the control term which produces the countering stick force.

The airborne diagnostic unit should display all defects and failures together with an unambiguous indication of the sources of the defect to LRU level. Following the concept of registering a dormant sensor failure which is not isolated by the executive failure detection mechanism, the diagnostic unit should perhaps, assess the state of the FCS inside the thresholds used by the executive failure detection system.

For the monitoring system providing data to both displays, a monitored duplicate system may suffice. Automatic and continuous testing of these monitors is needed in order to flag to the pilot and diagnostic displays the monitor status, both working, one failed, both failed. Whether a duplicate display should be used is arguable.

The monitor system needs, therefore, two computers which can be continuously tested in flight. These computers can be straightforward hardwired analogue/logic devices if the four FCCs are programmed to perform the complicated logic. The alternative of using two additional programmable digital computers for this purpose is attractive since it reduces the additional complex programming of the four FCCs and makes it easier to change the monitor program as mission, flight tasks or aircraft changes are made.

The two additional computers that are considered essential for the monitoring task can be used, with little increase in complexity, for the voter monitors for the two actuator lanes in the duo-triplex actuator system that are not provided for by the four FCCs (see section 4.1).

4.5 Stick and pedal designs for a future aircraft

The use of a miniature side controller in FBW aircraft such as the devices flown in the Avro 707 in 1964 and more recently in the Hunter in the UK and the YF-16 in the US, illustrate the potential of future FCS in providing improved pilot inceptors. There are disadvantages with small controllers; difficulties in installing devices for pilot trim, gun firing etc.; problems if the pilot's hand/arm is incapacitated. A larger, central and more conventional stick may be more appropriate for some aircraft; but the interface with the electronic FCS will be easier than in conventional mechanical systems, decreasing weight, size and complexity within the cockpit. These sticks can be designed to be easily replaced (as an LRU). Similar features and advantages apply to pedal and throttle lever designs.

Because the FCS will provide automatic trim in some modes, it may be desirable to reconstitute artificial trim cues at the stick and pedals but this is difficult with miniature sticks. Thus, for example, if the aircraft plus system acts to maintain attitude on the approach, speed variations could be used to vary the stick feel, force or deflection. This is related to the control signals added as the aircraft approaches its control boundaries.

4.6 Built in test equipment (BITE)

There is no need for special in-flight BITE for any subsystems or functions used continuously from take-off to landing since the systems described are designed to survive two or more failures. It is needed for those sensors, programs and subsystems not used continuously, e.g. the monitoring system associated with status displays, and task oriented control functions.

Pre-flight BITE is essential and has been developed for some digital systems, e.g. the Sea-King autostabiliser. Most of the functions are automatic but some important ones need the pilot's input, e.g. stick movement that checks motivator movement is that expected. It is this pilot operation that increases the time taken by the pre-flight BITE to about ½ minute. A suitable pilot's display is required to give indication of 'GO' or "NO-GO' and to indicate pilot's pre-flight actions. Any defects should be sent via the monitor system to the diagnostic display so that faults are isolated to LRU level.

4.7 Electrical power supplies

Since the digital computers can be deranged rapidly, the smallest power supply interrupt would cause loss of the aircraft. Moreover, these processors and the executive monitoring functions will lose all stored signals on power interrupt, and these are flight critical (see also the discussion on EMI and lightning in section 5.7).

The only solution appears to be the use of batteries to sustain power for 5-10 minutes so as to overcome the engine out case and to allow time for pilot ejection at the extreme case that power cannot be reconnected.

4.8 Connecting cables

The choice of signal lines is between electrical or optical fibre cables. At first sight, optical transmission appears very attractive in providing greater protection from interference (EMI) and lightning. Although the development of optical fibres and optical connectors has been rapid over the last few years, their use increases significantly the amount of electronic equipment. At each sensor and each actuator, analogue to digital conversion suitable for optical transmission is required.

Much of this additional equipment is situated at the extreme parts of the aircraft, e.g. close to motivators, where the increased weight is unacceptable, and where the electronic equipment will be in a severe environment. For these reasons, optical transmission systems may be more prone to EMI and lightning than electrical transmission systems. At the present time, with limited experience, it is difficult to judge which should be used. Electrical transmission is arguably the preferred solution for the next generation of aircraft because of the increased weight and complexity of the optical system. The development of digital sensors and actuators may change this.

Another development may alleviate the difficulty in the future; the combination of signals at extremes of the aircraft, for common transmission around the aircraft. Redundancy and integrity considerations preclude this option for aircraft FCS until it has been used with less critical systems but it could be attractive in future aircraft with a large number of motivators.

5 FAILURE EFFECTS AND CORRECTION: THE ACHIEVEMENT OF HIGH INTEGRITY

For many years we have been faced with the problem of achieving, demonstrating the achievement, and convincing certificating authorities that we have achieved the integrity requirements for electronic FCS.

Exhaustive testing is impractical due to the magnitude of the task (10^7 hours is about 1200 years) and, in any case, what matters is the reliability and availability in-service use where conditions are different from ground rigs whatever measures are taken to simulate as closely as possible in-service conditions.

It is necessary to augment any testing by a critical failure effects analysis, highlighting situations of concern and finding means to correct for problems. Such analyses in themselves do much to increase confidence, despite the fact that difficulties and problems are deliberately and critically examined. It is difficult to gauge the interrelation between the amount of testing, particularly statistical testing, and the degree to which a critical failure effects analysis is taken. The current trend is a reduction of statistical testing but not elimination; the use of search procedures to find the worst case in a set of statistical values is being developed in the UK.

For this paper, detailed discussion of failure effects and correction is limited to certain problems that have arisen during recent investigations in the UK on full time digital FCS. In a short paper, an exhaustive general treatment is impossible but the more critical aspects are mentioned. Despite the brevity of section 5.6, the mechanical design aspects have been with us for a long time and are believed to remain the most important in terms of flight critical systems.

5.1 Inter-lane synchronisation

When a failure occurs in a multiplexed system, it must be detected and isolated as quickly as possible. Problems arise if a failure is undetected (dormant) and a second like failure occurs. The failure detection mechanism must be chosen to safeguard against falsely failing a correctly operating lane or component and against failing to detect and isolate a failed lane. With analogue systems, allowance must be made for the tolerances of different lanes leading to difficulties in selecting thresholds which define the failed state.

The system advantages of employing digital technology is the greater accuracy with which calculations are made and the greater ease with which more complex algorithms can be programmed. However, the systems are hybrid, Fig.8, analogue to digital, then digital to analogue. The accuracy of the digital process can be realised only if the computers are synchronised and all inputs are identical or nearly so.

Two synchronisation algorithms are required, establishment and maintenance. On power up, the program of the four computers will be at random. The establishment algorithm causes each computer to wait in its program until it receives synchronising data from the other computers. On receipt of this data, the program moves forward to a starting point approximately in synchronism with the other computers; and after this the programs cycles begin. Precautions are taken to ensure that the system exits from the establishment program if one or more computers is faulty such that synchronisation cannot be achieved.

The maintenance program is simpler. When correctly working, computers will drift apart since the separate clocks are not identical. The drift rate is small, corrections are necessary once per many program cycling periods. The synchronisation maintenance allows limited adjustment, if needed, once per program cycle. For this purpose, synchronisation data is transmitted by each computer to the others.

In flight, a computer fault could cause it to lose synchronisation. It is unsatisfactory to rely on monitoring the outputs of the FCCs to detect such a failure since the outputs may be near zero and remain so for a time long enough for a second synchronising fault to occur, i.e. two dormant failures. It is necessary to detect directly and flag a synchronisation fault.

Such a synchronisation fault could be transient. The synchronisation maintenance routine causes the faulty computer to return into synchronisation if it can but the flag to the pilot remains unless he takes re-setting action; the flag to the diagnostic display remains set for between flight inspection.

Although it may be remote, all computers may lose synchronisation in flight. The system continues to operate in this condition but, failure detection thresholds are increased so as to avoid false failure situations. As discussed below, this leads to an increase in transients on further failures.

Satisfactory but different synchronisation routines are applied in the YC-14 AFCS, and Sea-King helicopter autostabiliser, both triplex systems.

5.2 Transient during failure detection and isolation

The discussion here is restricted to consolidation of motion sensors required for Class (A) full time control, e.g. four pitch rate gyros. The principles apply to other failure detection parts of the system.

A sensor is correctly operating when it is within specified tolerances of noise, datum error and sensitivity. These three sources of error combine to form an instantaneous measured value, true motion plus error. The true motion, common to all sensors, is eliminated in the detection algorithm. The instantaneous value of all sensors are compared in each of the FCCs, each accepted or rejected as failed and a consolidate formed, e.g. average, for use in subsequent control law calculations. This consolidate is identical in each of the lanes so that further failure detection and isolation can be made accurately upstream of the sensor consolidation.

It is necessary for the failure detection threshold to be greater than the sensor's specified tolerance in order that correctly operating sensors are not falsely failed and isolated. In the situation shown in Fig.14, the failure detection and consolidation algorithms are averages. Each sensor output is compared with the average and if the error is greater than the threshold T it is failed, flagged and isolated. At time t_1, Fig.11, all four sensors are correctly operating with two close to the positive tolerance level $+E$, the other two close to the negative tolerance level $-E$. If sensor 1 fails towards the negative threshold, it is necessary for the threshold to be greater than twice the tolerance

level, $T = 2E$, in order to prevent the correctly operating sensor 2 being incorrectly failed before the failed sensor 1 is detected and isolated at time $t = t_2$.

During detection of the failure, the average value forming the consolidate varies from the ideal. The aircraft experiences and undesirable transient combining the pre-detection and the subsequent post-detection transient following isolation of the failed sensor. The form of the transient is shown in Fig.11, the average signal. The magnitude depends on the detection threshold and the system gain between sensor and state variable of concern, e.g. aircraft acceleration.

The threshold is selected to ensure acceptable aircraft transients for the worst combination of sensor errors (assuming these lie within the specified tolerances) and the aircraft plus system state across the flight envelope. For the first failure, the acceptable transient is that barely noticeable by the pilot for the worst case in order to avoid pilot concern and possible undesirable intervention. This determines the detection threshold and, through the detection and consolidation algorithms, determines the accuracy required from the sensors.

The averaging algorithms used for illustration are the most straightforward but not the best in terms of allowing an increase in detection threshold and, therefore, a relaxing of sensor accuracy with resulting use of less expensive and complex sensors. Many algorithms have been studied, some requiring considerable calculation feasible with a digital computer although requiring more store; unless there is a significant improvement, complex programs are avoided. In all known cases, there remains a difference between the specified tolerance and the detection threshold which is needed to avoid rejecting two sensors when only one has failed.

It is possible, therefore, for a sensor to be outside tolerance yet remain undetected, i.e. one or more differences between sensors exceeds the tolerance $\pm E$ but the failure detection algorithm cannot decide which sensor has failed. The effect of this on a particular flight is an increase of about 25% in the worst transient for a second failure, which is acceptable. It is also possible for the sensor in the dormant failed state to be detected and isolated just before the second failure is detected; i.e. two almost simultaneous failures detected.

However, it is essential to ensure that such a dormant failure does not remain over many flights. If differences exceeding the tolerance are flagged to the diagnostic display unit, the information is available for between flight maintenance. This is a particular case of 'non-executive' monitoring, i.e. the in-flight logging of system conditions which do not affect the integrity of the particular flight but which will affect the system performance and integrity if allowed to remain over many flights. This concept has been advanced before[4].

5.3 Skewed axes sensors

For three axes, 2-failure survival control, three orthogonal sets of quadruplex motion sensors is the conventional arrangement. The cost and weight of using 12 gyros together with associated connecting cables for signalling and power supplies led to the concept of arranging the sensors skew to the axes of motion and computing the required motion along the desired axes of motion by resolving the sensor outputs. Six sensors[2] aligned along axes perpendicular to the faces of a duo-decahedron yields 2-failure survival but the transients experienced on first and second failures are, for the worst conditions, 12 times greater than for the quadruplex orthogonal set. Therefore, in order to maintain the same transients, sensors with 12 times greater accuracy are required which increases the cost and complexity of each sensor.

In an alternative arrangement[5], Fig.12, eight sensors are aligned in pairs along the sides of a regular pyramid. The six differences between each pair of four leads to two measures each of the motion in the three orthogonal axes, i.e. the eight sensors are easily resolved into quadruplex sensing in each axis. Detailed analysis supported by confirmatory laboratory tests have shown that the transients on first and second failures are, in the worst case, 1.7 times greater than for the quadruplex orthogonal set, an acceptable increase. Interface with either quadruplex or triplex computing is straightforward.

5.4 Inter-lane data exchange

In order to consolidate sensor signals, data is transmitted by each lane to the others. The data received in one lane may not be identical to the data received in another if a fault occurs in the transmission, Fig.13. The output of the FCC receiving the erroneous data will differ from the outputs of the other computers and could be flagged as faulty due to an actual fault in the other transmitting lane. Moreover, if the error is large enough the sensor in the transmitting lane will be assumed faulty by the receiving lane only, leading to incorrect isolation of a sensor and a further difference in the FCC output. The fault remains undetected and if it is a slowly degrading fault, e.g. deterioration of power supplies in one lane, it could lead to false failing a second good lane.

One solution to this failure case involves careful comparative monitoring of the transmitted signals from each lane at the 'fan out' point. The monitoring function depends on the type of computer used and the method of inter-lane transfer but in all cases considered, additional hardware is required in the computer. A second partial solution is to compare the integrals of the control demand signals, the FCC outputs. These integral signals will be different only when there is an inter-lane fault and the integral values will slowly drift apart. Feedback of these signals as 'sensor inputs' reduces the effects of the error on the outputs of the FCCs. Referring back to the remote chance of losing synchronisation, the use of this integral monitoring term should reduce the inter-lane errors.

5.5 Programming a digital FCS

The control laws to be programmed divide naturally into those required for flight control and those for system control (synchronisation, sensor consolidation, failure detection, monitoring, BITE, etc.). The flight control laws will become more complex and need more store as the concepts outlined in Section 2 are implemented. There is a tendency, at the same time, to employ more complex system control laws in

order to reduce cost, size, weight and equipment complexity at the expense of a 'bit more program store'. In a typical FCS, 15% of the program store is used for flight control, the rest for system control and this ratio is likely to remain fairly constant.

Programming consists of a number of stages, shown in outline in Fig.14. Initially, aerodynamicists, structural experts, control law engineers and systems people prepare their requirements separately. In the next stage, all requirements are formulated in a single flow diagram. This formulation of all requirements is, perhaps, the most critical area and it is imperative that as the detailed flow diagram is prepared there are continuous checks back to the separate specialists. The specialists must be responsible for this back-check and devise their own methods of testing. The more detailed the final flow diagram the less likely are software errors in the next and final stage; this more detailed specification is done at the expense of making the specialists back-checks more complex.

Rules controlling programming from the detailed system requirements to machine code have been formulated and used in the UK: and will, no doubt, be improved as experience grows. Modularisation of software is important, the modules bearing a one-to-one correspondence with different control law modules and, ideally, with specified PROM rows.

It is not possible to test modules, groups of modules or the complete program exhaustively for all possible input states simply because the number of possible states approaches infinity. A certain amount of statistical testing may be desirable and may give some confidence. Certainly, all possible paths through modules, groups of modules and the total program must be tested for maximum and minimum inputs and combination of these. Such tests are done by different people to those who wrote the program. Other techniques are used to help 'prove' the program, to establish confidence that the software is correct. One such technique is to automatically derive the detailed flow diagram from the machine coded program. This closes the test loop around the software part of the overall program. These and other recently developed methods indicate that mistakes and misinterpretations of the detailed flow diagram, the system specification, are more likely to be causes of programming errors than incorrect software.

A rigorously applied system of change request and implementation is essential. The relative ease with which a program can be changed will lead to confusion, mistakes and delays unless a rigorous process is applied. Such a procedure has been developed and applied; and from the experience gained, improved rules governing such changes have been derived.

The term 'visibility' is often used in relation to the confidence that the software is correct. General concern about the possibility of all lanes having a common software error leads to the need for the machine coded program to be fully understandable by people with little expertise in the subject. Preferably the separate specialists should be able to back-check from machine code to their basic requirements. Straightforward programming is essential for this, even at the expense of using more store, avoiding programming 'tricks' that make the program less easy to follow. Ideally, choice of digital processor, instruction set and language should be made, for a particular system, from this visibility aspect as was done with the Concorde air-intake system.

5.6 Mechanical design

At the other extreme to the software problem is the treatment of mechanical design throughout the FCS. Current specifications used for the selection of components in in-service FCS may not necessarily reflect the criticality of full time operation. It is certain that successful systems will involve painstaking selection and testing of the most appropriately designed components for the task. In particular, flight clearance test programmes will have to be comprehensive in terms of duty cycle and environment.

5.7 Electromagnetic interference and lightning strikes

The discussion so far on failure effects and correction has not referred to the integrity requirements outlined in section 3. For the discussion on EMI and lightning the suggested alternative approach will be used.

Interference is likely to cause failures of some kind more often than 5×10^{-8} per flight hour. Total destruction of all four FCCs will cause loss of aircraft with no hope of recovery. The chance of such total destruction is probably less than with in-service (mainly analogue) systems, FCS and others, because improved technology and methods afford greater protection than before. The sum of all flying hours with this previous technology is large and gives some confidence that the extreme event will be rare.

However, digital systems may well be more prone to derangement and difficulties in recovery after derangement than previous systems. What caused (unmonitored) transients in previous analogue systems could result in loss of aircraft unless precautions are taken.

Derangement of one or two lanes is likely to be satisfactory with the systems discussed, especially if the pilot is allowed to attempt to re-engage after loss of lanes. Loss of synchronisation in all four lanes has been discussed and this is not a problem in terms of the suggested integrity approach. What happens, however, if three or four computers are deranged for a short period of time? We cannot assume, with evidence available, that this will occur less frequently than 5×10^{-8} per flight hour, whatever precautions we take.

The outputs of the four FCCs are monitored and derangement will be known quickly even if the monitors themselves are deranged. Provided dedicated electromechanical switches are used, which are interference free, the deranged outputs to the actuator lanes can be switched off before the motivators are erroneously moved by significant amounts. Assuming this can be done, the risk of aircraft loss after derangement (target 10^{-4} per flight hour) will be satisfactory provided:

(a) the interference does not last long enough for the uncontrolled aircraft to lose total control;

(b) control can be regained quickly after the interference has ended.

The second condition (b) implies that dc signals should not be held on the digital computers. With the actuator outputs fed back to the computers, the latter could be re-initialised with respect to this signal. It is unlikely that this is sufficient to reduce the risk of aircraft loss after derangement to be within the target, 10^{-4} per flight hour. A supplementary precaution may be needed, the storage of dc signals on a mechanical device preferably within the actuator itself. Fast trim transfer within the FCS is needed using techniques already investigated in the UK.

This general discussion does not help prove that the fatal effects of EMI and lightning can be overcome. It points to the need to find how often it occurs, how long it lasts if it does occur, and the development of electromechanical devices to permit the system to survive.

6 EFFECTS OF FCS COMPONENT LIMITATIONS

The performance of aircraft plus system may be limited by factors associated with imperfections and limitations in FCS components, e.g. noise on sensor outputs, lags and rate limits of actuators etc. The design of flight control laws must include the effect of such limitations because their inclusion leads to considerable coupling of the aircraft modes of motion with the modes introduced by actuators, sensor filters etc. This design problem is outside the scope of this paper but a brief discussion of the practical issues is given below.

6.1 Motion sensor noise

The output of motion sensors is a sum of the true motion, instrumental noise and undesirable aircraft motion, e.g. pick-up of a structural mode by a rate gyro. Appropriate siting of sensors minimises such noise but the ideal position is often unavailable in practice and can never eliminate the pick-up of all structural modes. Some form of filtering is needed, the usual method being a notch filter tuned to the anticipated troublesome mode.

With some motion sensors such as accelerometers, where for reasons of cost and integrity strapped down sensors are desirable, lower frequency noise or datum errors have to be eliminated by mixing with other sensor outputs; using, for example, high order linear complementary filters. In addition, undesirable motion such as those due to attitude dependence must be removed by appropriate correction to the output using data from other sensors. These complexities, and the cost of providing redundant sensors, lead the control law designer to attempt a compromise using fewer sensors at the expense of some loss in performance of aircraft plus system.

An interesting and important example of this tendency is the use of integral pitch rate rather than incidence to provide the necessary stiffness in an aircraft with negative static margin. Another example is the use of strapped down normal accelerometers rather than gust probes to provide improved ride in turbulence in the vertical plane using direct lift (DLC).

6.2 Actuator response characteristics

Detailed modelling of the actuator is required to analyse system plus aircraft behaviour including local structural effects at the control surface. For the flight control law design, simplification can be made. Typical for 2-failure survival actuators that have been developed in the UK are: a second order lag, natural frequency 120rad/s and relative damping 0.5; first order lag, time constant 0.05s; and 60°/s rate limit. Improvements can be made, if required, but at greater cost and complexity.

In addition to the lags introduced by the actuator, filters must be added to ensure that sensor noise and noise from other parts of the system do not continuously excite the actuator causing unnecessary wear. In most cases, this is a more severe requirement than the need to include filters so as to prevent noise producing undesirable aircraft motion.

The performance of the 'auto-loop', Fig.1, is the product of Control (1) and the aircraft, particularly the control effectiveness of the surface. Performance limitations are often due to unsatisfactory control effectiveness. An example is the limitations to the decrease in normal acceleration due to turbulence obtained with DLC; due to a combination of actuator rate limit and control surface effectiveness.

6.3 Possible advanced control policies

These practical difficulties in the design of flight control laws lead to the study of control policies more advanced than the traditional fixed linear laws. Theoretically, it is possible to estimate the state variables required from available measurements using advanced techniques such as Kalman filtering. However, time is required to estimate and eliminate noise and, for flight control, time is not available.

An alternative, mentioned in section 2.4, is based on the concept that the noise effects could be allowed to increase when, and only when, the rate of error signal is large, e.g. during a pilot command for a rapid rate of change.

7 CONCLUDING REMARKS

The exploitation of full time FCS in combat aircraft will lead to improved flying qualities through the use of variable and changeable control, including task oriented control in which the pilot will select the aircraft plus system optimised for different high performance flight tasks. Such systems need to be digital.

This exploitation of FCS leads to greater complexity not so much in the system engineering but in gaining confidence that the required integrity will be achieved. What the integrity should be for a high

performance combat aircraft is arguable but it is likely that a 2-failure survival system is needed. Given this, the trade-off between complexity in equipment and complexity in 'software' is difficult to judge. On the one hand, factors such as size, weight and cost should be minimised; on the other hand, the more complex the control laws, for both system and flight control, the more difficult is the 'proving' of the software and the less visible is the program for certification purposes.

This paper has attempted to survey the current state-of-the-art and thinking on such systems, design, engineering and test. It has not been the intention to define a specific solution; there are many possibles.

Table 1 Control for aircraft in low level, high speed flight

		Auto-loop		Pilot loop	
		Possible requirements	Possible control techniques	Possible requirements	Possible control techniques
(1)	Prolonged flight	Maintain attitude, height and forward speed. Good 'ride', minimise pitch rate, accelerations and vertical velocity errors due to wind	Use of DLC to minimise effect of wind	Precise height control for small pilot demands. Rapid acceleration for large demands. Flight boundary limiting, including ground warning	Response varies with demand. Use of DLC to improve response for small demands
(2)	Tracking ground target	As (1)	As (1)	Precise attitude control or precise control for available weapon. Multi-axis blended control appropriate for task	Response varies with weapon. Use of DLC as (1)
(3)	Combat	Maintain aircraft trim state (attitude, rate of dive, forward speed, incidence etc.)	Blended controls with appropriate motivators including thrust control	Light stick. Rapid response to stick, pedals, throttle levers etc. Control boundary limits. Multi-axis blended control appropriate for task	Self adaptive control (2)

Table 2 Summary of variable and changeable control concepts

	Concept	Remarks
(1)	Changes during development	Uncertainty in aircraft characteristics. Difficulties with flying qualities
(2)	Changes during service	Fuel, stores, mission changes. Improved flying qualities
(3)	Variations with aircraft and FCS state	Scheduled changes to auto- and pilot-loops. Control and flight boundary limits. FCS failures.
(4)	Variations with Amplitude and rate of control	Improved aircraft response to pilot demand. Increased speed of auto-loop when required. Self-adaptive control (2)
(5)	Pilot's selectable task oriented control	See Table 1 for example

Table 3 Sensors and transducers for FCS

	Sensor/transducer	Remarks
(1)	Rate gyros	Three axes control: pitch, roll, yaw rate
(2)	Air data	For scheduling control
(3)	Accelerometers	Lateral and normal: improved auto-loop control
(4)	Incidence	Datum in auto-loop control. Flight boundary
(5)	Side-slip	Pilot loop control
(6)	Stick pick-offs	Two axes control
(7)	Pedal pick-offs	
(8)	Linear variable differential transducer	Actuator feedback for voter-monitor

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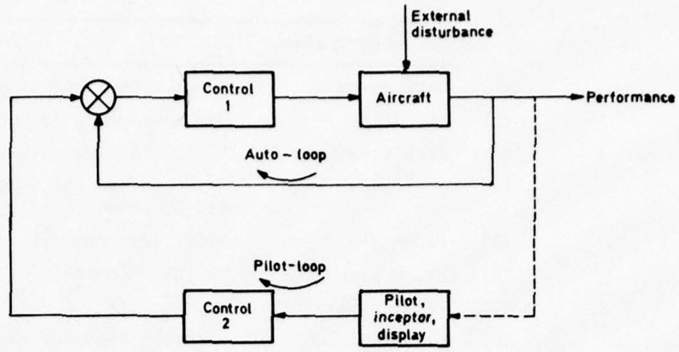


Fig.1 Simplified control loops for any FCS

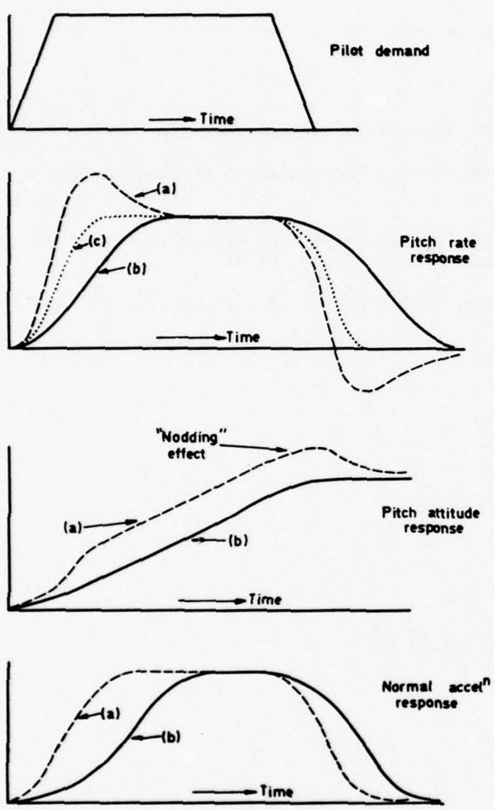


Fig.2 Conflict between pitch rate and acceleration responses

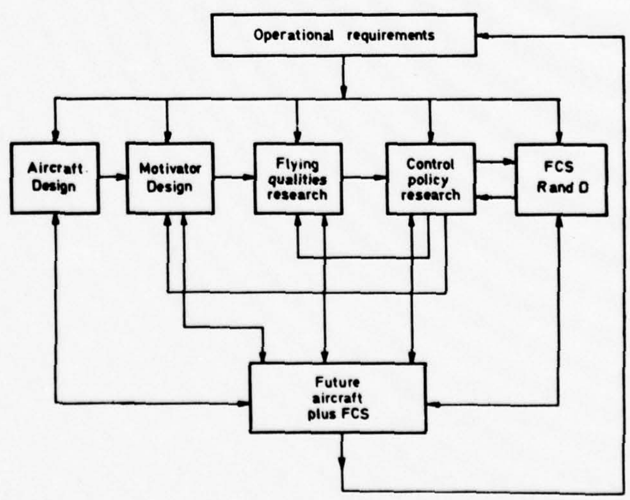


Fig.3 Control loops in design of aircraft plus system

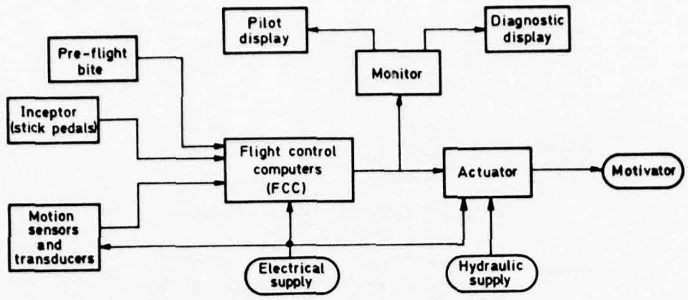


Fig.4 Sub-systems of a typical FCS

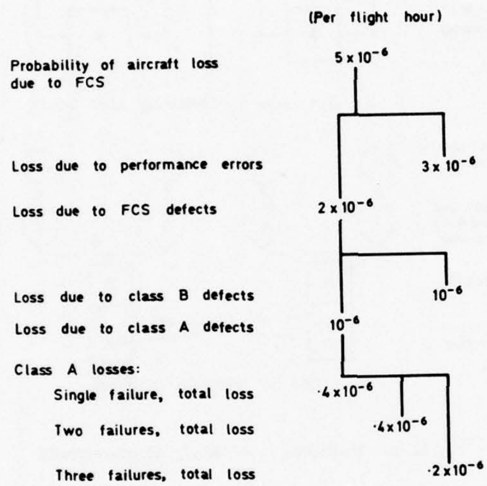


Fig.5 Division of loss rate

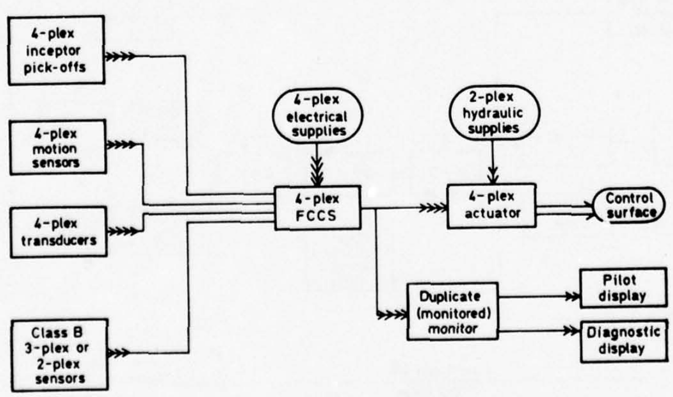


Fig.6 Outline of redundant FCS for full time control

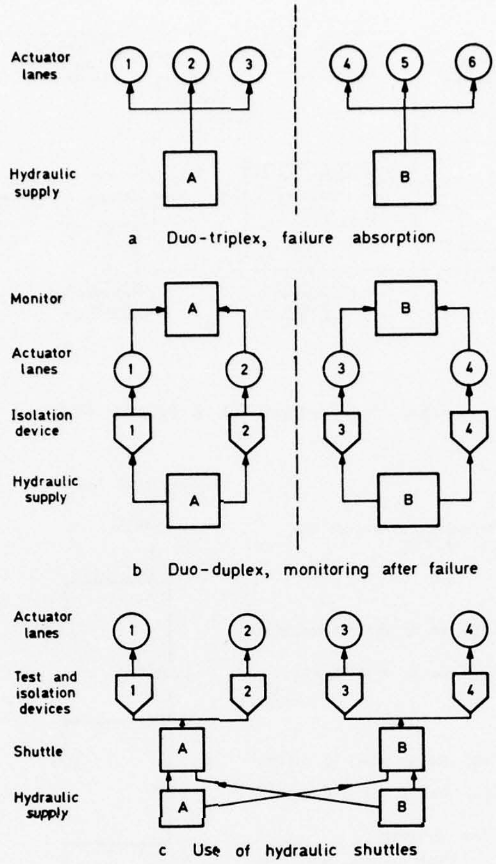


Fig.7a-c Multiplex actuator arrangements

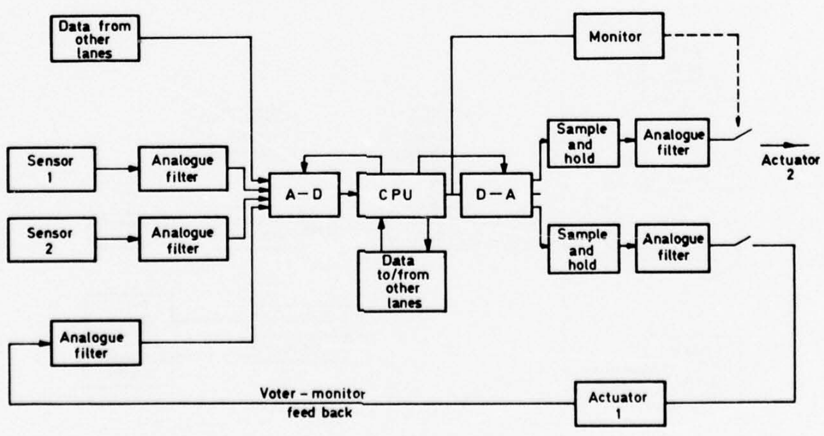
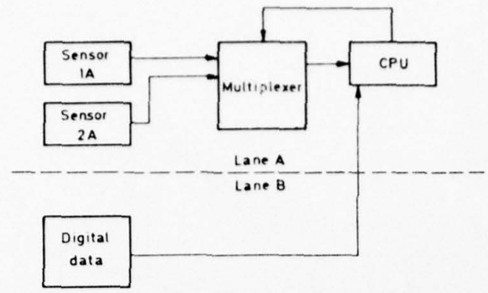
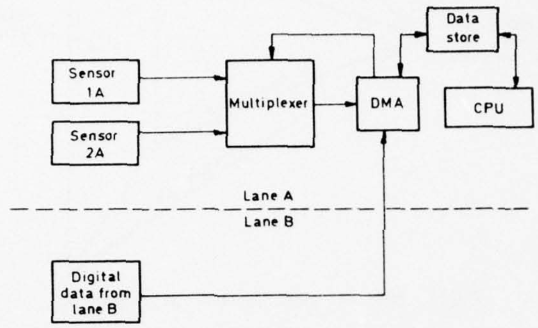


Fig.8 Outline of single lane of digital FCS



a Direct data access



b Direct memory access

Fig.9a&b Choice of inter-lane data exchange

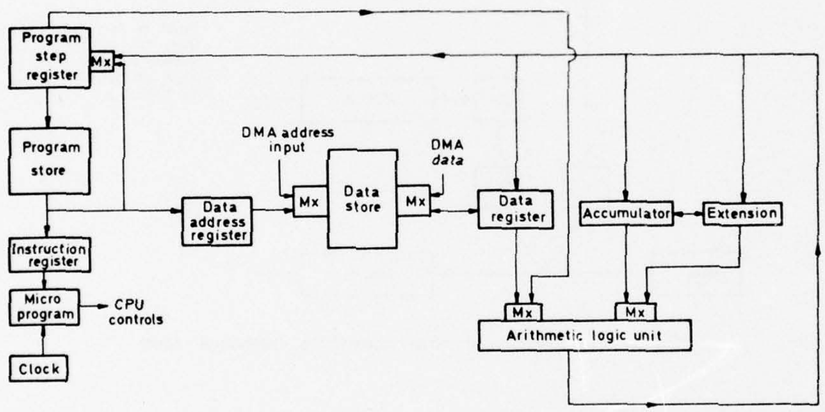


Fig.10 Outline of a central processor using direct memory access

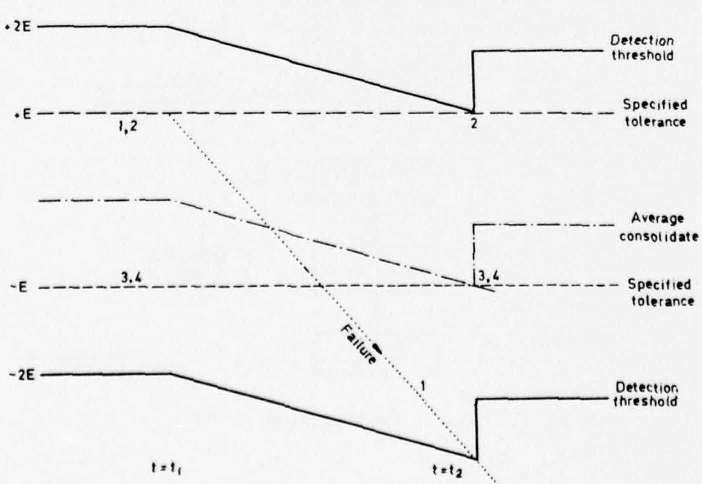


Fig.11 Principles of failure detection and isolation

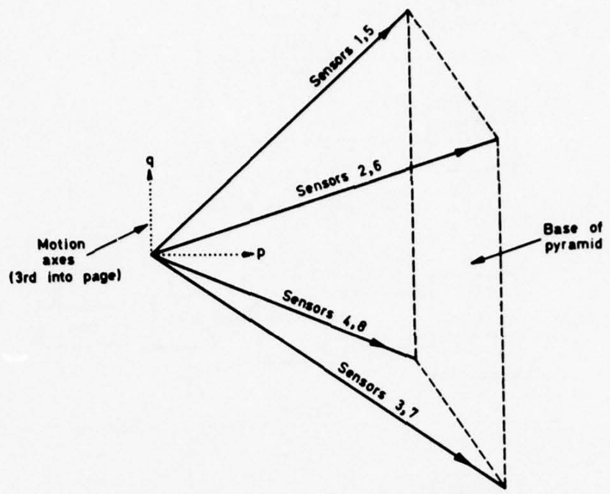


Fig.12 Skewed axes sensor arrangement

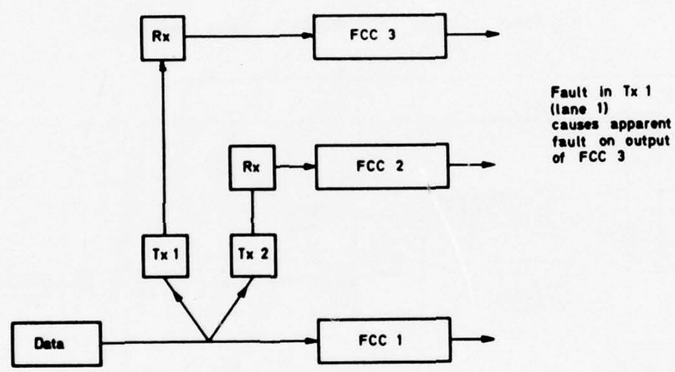


Fig.13 Explanation of inter-lane data exchange fault

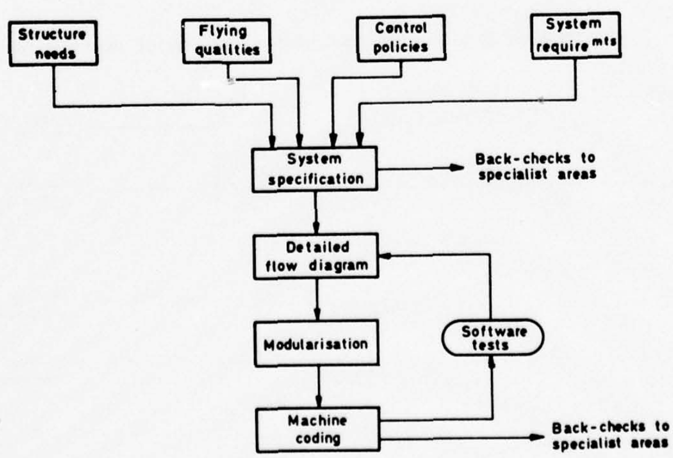


Fig.14 Programming a FCS

THE NEED FOR TASK ORIENTED CONTROL LAWS

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INTRODUCTION

In this lecture we will address the need for task oriented control laws. When a control system designer is asked to define a set of control laws for an aircraft, he may quite properly ask: What is it that I am to control? What is the performance measure which we want to minimize? Traditionally the objective of an aircraft control system design has been to provide damping of the free response of aircraft. Systems of this sort have been described as stability augmentation systems. More recently, systems have been built which are properly termed maneuver command systems.

In traditional stability augmentation system design objectives are posed as requirements on dutch roll and short period damping and frequency. For the maneuver command systems, the requirements are posed as command following capability either in time domain or frequency domain terms. These were a first effort in task oriented control where the problem was posed as a particular response to a step function.

In the modern combat environment, aircraft control system requirements for weapon delivery are much more severe then previously experienced. Aerial combat is characterized by multi-aircraft engagements with only fleeting opportunities for gunnery attack. Missile attacks will be difficult because of the danger of destroying one's own forces. Air-to-ground attack is very dangerous because of the capability and density of anti-aircraft defensive systems. The common requirements arising from this environment are on maneuverability and time.

The aircraft dynamics, as determined by the control laws, must provide for attacks where the time allowed for weapon aim becomes exceedingly short and the attacker must be continuously evasive with respect to the most probable defensive systems. Survivability may well be inversely proportional to the time spent in predictable flight.

The prediction and control system made up of aircraft, weapon, target, and pilot must be optimized to deal with these requirements. The aircraft control system is one of the tools for this optimization. The problem of synthesizing a task oriented control law then begins with the dynamic modeling of the total system. The need for task oriented systems should therefore be apparent from the differing requirements of the various tasks.

AERIAL GUNNERY - TASK DESCRIPTION

Typical aerial gunnery targets are characterized in Table I.

Table 1.

TARGET CHARACTERISTICS	
Vulnerable Area	5 - 30 m^2
Range	300 - 1000 m
Speed	200 - 2000 kt
Turning Capability	5 - 9 g
Altitude	0 - 15000 m
Value (Initial Cost)	$\$10^6 - 10^7$

We see that target value is high and target vulnerable area is large.

The target value and its capability for destruction are so large as to dwarf the cost of expendables. Conservation of missiles and cannon shells should be determined by mission requirements only.

Because of the great agility of typical targets, it is expected that compromises between attacker maneuver control and gun pointing may be required in order that a shooting opportunity may be gained. In other words there may not be any separation possible between air combat maneuvering and precision gun pointing.

The target dynamic model in terms of attacker line of sight co-ordinates is conveniently derived in vector terms. The vector angular rate of the target line of sight is given by:

$$\dot{\bar{\Sigma}}_T = \bar{S} \times \left(\frac{\bar{V}_T - \bar{V}_A}{R}\right) \tag{1}$$

The vector angular acceleration of the target line of sight is

$$\ddot{\bar{\Sigma}}_T = \frac{1}{R}\left(\bar{S} \times (\bar{A}_T - \bar{A}_a) - 2\dot{R}\,\dot{\bar{\Sigma}}_T\right) \tag{2}$$

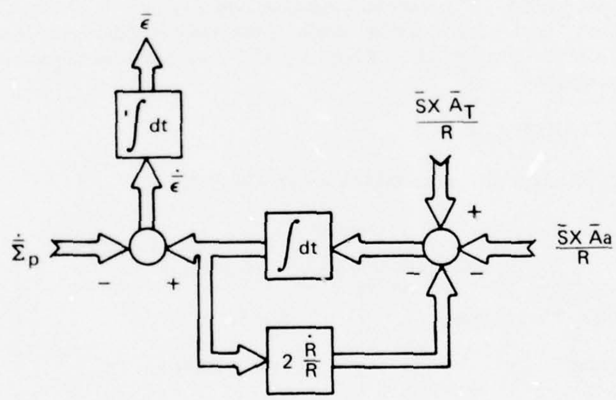
Examination of (2) shows the fundamental instability of the kinematics. For negative range rates i. e. : closing attacks, the LOS rate is divergent with a time constant given by:

$$T = \left(\frac{-R}{2\dot{R}}\right) \text{ sec.}$$

This term is unimportant in steady low closure rate attacks but quickly begins to dominate high closure attacks.

Figure 1 illustrates the kinematic equations.

A combination of the encounter dynamics with those of the aircraft and the gunsight provides a set of differential equations which describe the total controlled element. The objective of the flight control system design is then to find control laws which augment and alter the vehicle dynamics in such a way so that the pilot can use his aircraft effectively.



$$\bar{\epsilon} = \begin{pmatrix} O \\ \epsilon\ell \\ \epsilon m \end{pmatrix} \quad (\bar{S}X\,\bar{A}_T) = \begin{pmatrix} O \\ -A_{Tm} \\ +A_{T\ell} \end{pmatrix}$$

$$\dot{\bar{\Sigma}}p = \begin{pmatrix} O \\ \epsilon_{p\ell} \\ \epsilon_{pm} \end{pmatrix} \quad (\bar{S}X\,\bar{A}_a) = \begin{pmatrix} O \\ -A_{am} \\ A_{a\ell} \end{pmatrix} \cong \begin{pmatrix} O \\ -A_z \\ A_z\,\Delta\phi \end{pmatrix}$$

Figure 1. Kinematic Relationship Aerial Gunnery

Figure 2 is a block diagram of the pertinent unaugmented lateral-directional dynamics in an aerial gunnery encounter.

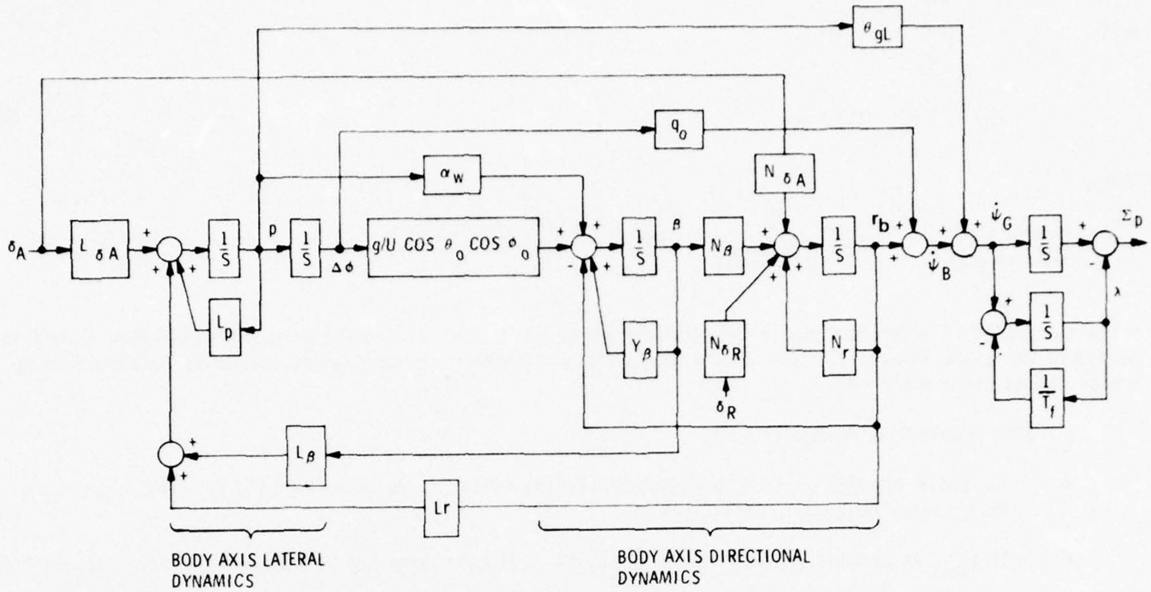
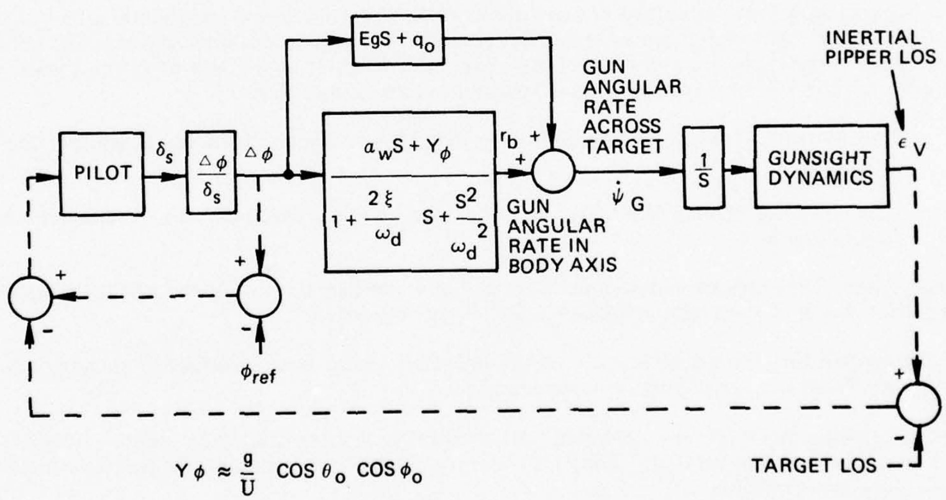


Figure 2. Lateral Directional Dynamics

In simplified form, the dynamics may be portrayed as shown in Figure 3.



$$Y\phi \approx \frac{g}{U} \cos\theta_o \cos\phi_o$$

Figure 3. Simplified Directional Gunnery Control Model

If somehow the directional dynamics block shown in Figure 3 could be made to have unity denominator, the traverse inertial angular rate of the gunline ($\dot{\psi}_{gun}$) would be

$$\dot{\psi}_{gun} = \Delta\phi \; (\theta_{gL} + \alpha_w) \;\; s \; + \; (q_o + g/_U \;\; \text{Cos}\;\theta_o \; \text{Cos}\;\phi_o) \tag{3}$$

For steady pitching situations

$$q_o + g/_u \;\; \text{Cos}\;\theta_o \;\; \text{Cos}\;\phi_o = (\frac{aN}{U})_o \tag{4}$$

Also note that

$$\frac{aN}{U_o} = - Z_\alpha \alpha_w \tag{5}$$

and

$$\alpha_w + \theta gL = \alpha_{gun} \tag{6}$$

Thus

$$\frac{\psi\ gun}{\Delta\phi\ command} = \left(\frac{\Delta\phi}{\Delta\phi command}\right) \left(\frac{aN}{U}\right)_o \frac{\left[1 + s\left(\frac{\alpha_{gun}}{\alpha_w}\right)\frac{1}{-Z_\alpha}\right]}{s} \tag{7}$$

When combined with the kinematic relationship given in (1) and (2) and the gunsight dynamics, equation 7 portrays the pilots traverse control task under the assumption of unity denominator in the directional dynamics as previously stated.

Several points are worthy of note.

- An inner manual control loop on differential roll attitude closed on the target removes an integration from the control task.
- If α_{gun} is greater then or equal to α_w the roll rate coupling is beneficial to the piloting task.
- If α_{gun} is less then α_w (depressed gun line) this must be accounted for in the task oriented control law.
- The gain from roll changes to traverse changes is proportional to total lift acceleration divided by speed.

The control task just described is not simple since the pilot has a multi-loop task but it can be effectively done. If the assumption of unity directional dynamics is not met and considerable additional lag is introduced, the traverse gun control task becomes difficult especially at lower angles of attack and turn rate. Thus two requirements on directional control laws are:

- Roll dynamics should be augmented so that high bandwidth bank angle control can be achieved.
- A directional control law which minimizes slip angle response to roll changes should be implemented.

Some other observations which pertain to the task are that the full speed altitude, angle of attack, and load factor range of the flight envelope must be considered.

It is apparent that the requirements on lateral-directional control laws for gunnery are not inconsistent with those for air combat maneuvering.

There is some evidence that optimum roll bandwidth and sensitivity for gunnery tasks are different than for normal bank angle control. Additional responsiveness is desirable when roll control is an inner loop to traverse gun pointing.

The pitch axis control task for air to air gunnery can be described as a modified attitude tracking task. Gunsight dynamics may make the gunsight pipper behave somewhat differently than the gun line itself.

Figure 4 is illustrative of the dynamic equations. The response of the pipper line of sight to elevator inputs including the effect of a conventional disturbed reticle sight in transform terms is

$$\frac{\Sigma p}{\delta e} = \frac{M_\delta (S - Z_\alpha)}{S(1 + ST_f)\left[S^2 - (M_q + Z_\alpha + M_{\dot{\alpha}})\ S + (M_q\ Z_\alpha - M_\alpha)\right]} \tag{8}$$

Control requirements vary somewhat as a function of gunnery technique. In typical fighter vs fighter engagements steady tracking opportunities will be the exception. Preferred tactics call for the pipper to slide through the target preferably from an overlead position.

Since the system does not require optimization for tracking it is useful to factor in considerations from air combat maneuvering. In this area we require

- Fast well damped load factor response
- Protection against exceeding aircraft load factor capability
- Stall inhibiting/stall prevention or
- Controlability in the stall region.

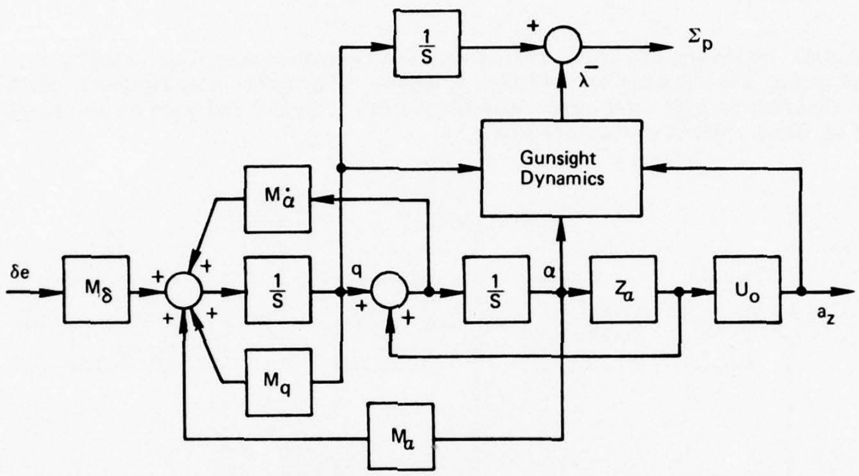


Figure 4. Pitch Air to Air Gunnery Dynamics

PRECISION AIR TO GROUND GUNNERY - TASK DESCRIPTION

In this lecture we consider air to ground attack with a high velocity large caliber aircraft cannon such as the GAU-8, 30mm cannon on the A-10. In this employment, the gun is being used as a precision weapon rather then a strafing weapon. Air to ground targets pertinent to precision gunnery attacks are characterized in Table II.

Table II

TARGET CHARACTERISTICS	
Vulnerable Area (30-40 mm)	1-2 m^2 Tank 2-8 m^2 Truck
Range	1000-3000 m
Speed	0-50 KT
Turning Capability	.25g
Altitude	0-2000 m
Value (Acquisition)	$\$10^4 - 10^5$

Targets are characteristically small and armored. The defensive environment is formidable consisting of guided missiles and anti-aircraft guns of various calibers. Target value is small relative to attacker. High attrition rates are unacceptable on any long term basis. The gun is a very desirable weapon in a war of attrition since other precision weapons can easily cost more then the targets. On a long term basis it is unattractive to expend high cost weapons to destroy low cost targets.

Two kinds of attacks are envisioned. The first is the low altitude-high speed attack where the primary defensive tactic is surprise. The basic control requirement is quick response with a desire to pop up and aim at a target in a manner of seconds. Firing range is typically short, say under 1500 meters. This tactic is appropriate for attacks on tanks, light armored vehicles, and trucks. If anti-aircraft weapons must be attacked directly without benefit of surprise, attacks must be made from longer range, perhaps as much as 3000 meters. Maneuvering must be sustained at all times to avoid defenses.

To be effective at ranges in the order of 3000 meters against small ground targets, it is necessary that a sighting capability in the order of 1 - 2 mils be employed with a correspondingly accurate control system. Both the sight and control capabilities are within the current state-of-the-art for fixed-gun figher aircraft.

The longitudinal dynamics has been presented in the simplified way illustrated by Figure 5 to show how recoil, wind gusts, and the pilot all enter the problem. Examination of Figure 5 indicates that there is no significant filtering on high frequency disturbances due to recoil and wind gusts except that which can be provided by flight control system feedback.

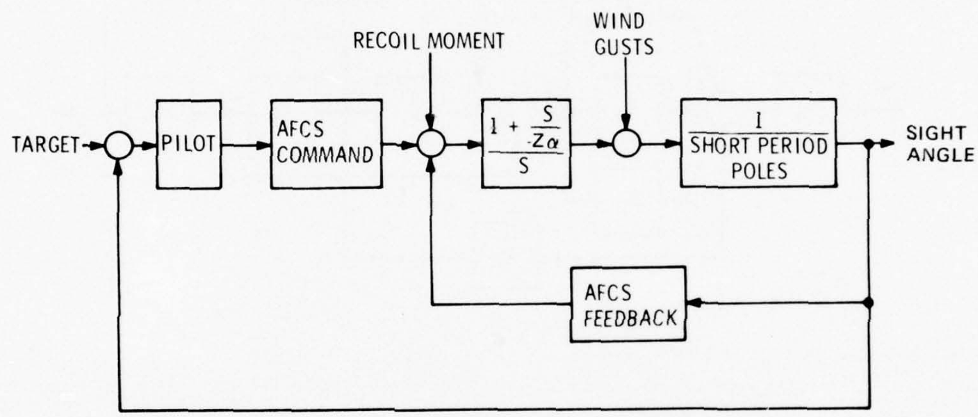


Figure 5. Air-to-Ground Gunnery Longitudinal Dynamics

It can easily be shown that high gain feedback of sight angle rate (which is aircraft pitch rate) can overdamp the aircraft response to eliminate resonant amplification of the recoil moment, and to further scale down the steady state rate response to applied moments. This type of feedback also effectively eliminates wind gust disturbances as a significant problem.

Since there exist two degrees of freedom in the flight control system mechanization, i. e., command and feedback, the disturbance rejection just discussed can be achieved and the system can be properly conditioned with respect to manual control or tracking dynamics. Tracking results with the properly mechanized system are limited primarily by optical resolution, and magnification may be required to realize ultimate performance.

The resulting system does not provide responsive control of the velocity vector because of the overdamped pitch response. However, advantage can be taken of the limited maneuverability required in the aiming and firing stages. Deliberate nonlinearities can be introduced in the system so that reasonable velocity vector control responsiveness can be maintained during acquisition and escape maneuvers. This nonlinearity can take the form, for example, of limiting the authority of the high gain feedback path. When a large maneuver is commanded this path limits thus removing itself from the dynamic problem.

Figure 6 shows the lateral-directional dynamics for the air-to-ground gunnery case. As one would expect, it has some similarities with that given for air-to-air gunnery. The principal differences are the absence of sight dynamics, the addition of rudder pedals as principal control inputs and the addition of wind gusts as a disturbance.

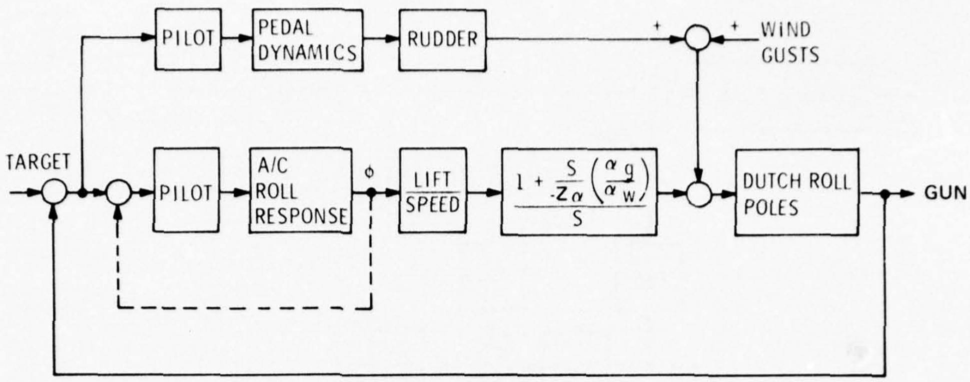


Figure 6. Lateral Dynamics for Air-to-Ground Gunnery

Precision tracking air-to-ground is made difficult by the low angle of attack common during the attack. This shows up as a small ratio of lift to speed in Figure 6. The lead term $\left[1+S/-Z_\alpha \frac{\alpha_g}{\alpha_w}\right]$ can cause control problems because α_w will be small and α_g may be negative. Negative α_g comes about because the gun may be depressed for tactical considerations. Sight dynamics are effectively unity thus removing that consideration. Further, target maneuverability which drives the air-to-air problem is a small effect in the air-to-ground attack.

Control solutions for the directional axis can take two approaches. For the case of an austere aircraft which does not carry an inertial system or a target tracker the control system must operate with certain restrictions. Since the effect of large sideslip angles cannot be accounted for in the gun sight the control system must be configured to minimize slip due to rolling maneuvers. The pilot can use rudder pull inputs to null gun pointing errors only to the extent to which he can account for the errors introduced by sideslip.

The error introduced by slip is approximately $\epsilon = \frac{U}{U + V_M} \beta$

If the gun line is depressed below the wing zero lift axis compensation must be introduced in the control system to move the aircraft roll axis down so that there is never a pendelum effect. Such an effect is devestating to rapid gun pointing.

In the case of the better equipped aircraft which has an appropriate fire control system, it is possible for the pilot to use any combination of rolling and slipping inputs as he desires.

BOMBING - TASK DESCRIPTION

The control task for a bombing is determined largely by the type of bombing system employed in the attack aircraft. A bombing system of a modern type which has inputs from an inertial navigator or a target tracker and appropriate own ship inputs will be considered in these discussions.

Fundamentally when a bomb is released it has for its initial velocity the intertial velocity of the attack aircraft plus modifications due to ejection impulse and flow field effects. It seems sensible to consider that the primary control problem for the pilot is control of the direction of the velocity vector. The pilot is required to perform tracking in the traverse axis and has only a timing problem in the pitch axis so as to effect a release when the solution cue goes through solution or a display pipper passes through the target. Some systems even automate the release.

The precision control task for the pilot is thus limited to controlling the traverse direction of the aircraft path.

Figure 7 illustrates the dynamic task.

If the directional control system keeps Ay negligibility then $\omega_T \sim \Delta\phi$

and bank angle is an inner loop to directional error control. Alternatively if the pilot can modulate side force (Ay) it can be an inner loop to traverse error.

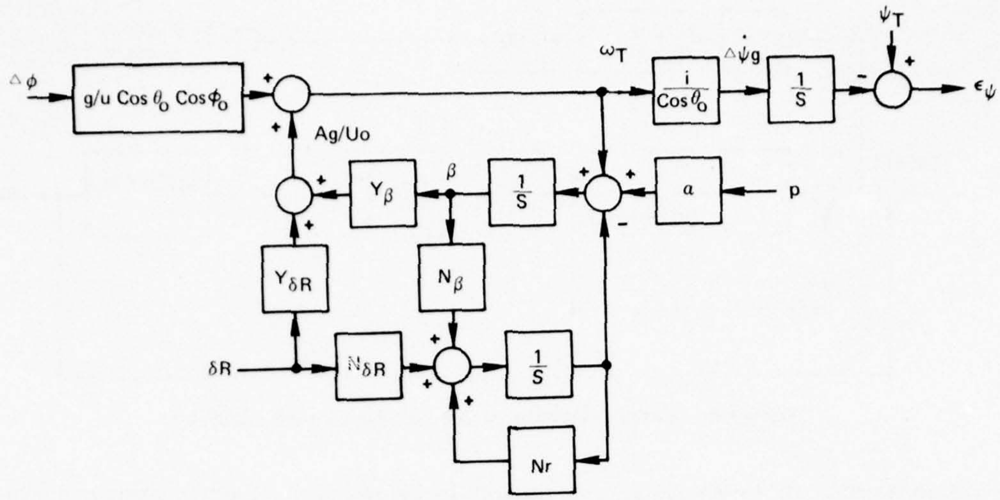


Figure 7. Directional Dynamics for Bombing

CONCLUSIONS

At this point it is appropriate to draw some conclusions. Several example weapon delivery problems have been examined and their requirements pointed out. Although they have not been discussed additional tasks requiring consideration for control purposes are refueling, landing, take off, formation, and optimum climb/cruise profiles.

The need for task oriented control laws becomes important when aircraft controlability is important to mission completion.

Previous system design requirements have been placed principally on stability which can be viewed as control of the location of the system poles. Task oriented control laws address the question of input-output relation which requires consideration of the location of the system zeros as well as the poles. It is indeed a control design problem as distinquished from a stability design problem.

The synthesis of a task-oriented control law is made up of several parts. The aircraft, the kinematics, weapon aiming dynamics, required guidance laws, and most important the pilot, all must be taken into account. In the preceding discussion some of these elements have been explored. The determination of the control laws is then possible.

Tradeoffs and compromises are to be expected in control system design. Since any given aircraft has several flight phases including task oriented control laws necessarily leads to a multimode system. A system of this sort must be carefully integrated so that pilot action is minimized. Less critical tasks may be compromised to reduce pilot confusion.

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SYMBOL LIST

$\bar{S}$	Vector along line of sight
$\bar{s}$, $\bar{l}$, $\bar{m}$	Line of sight co-ordinate set - quasi inertial
R	Range from attacker to target
$\dot{R}$	Range rate
$\bar{V}_T$	Target vector velocity
$\bar{V}_A$	Aircraft vector velocity
$\bar{\Sigma}_T$, $\dot{\bar{\Sigma}}_T$, $\ddot{\bar{\Sigma}}_T$	Target line of sight vector angle, rate, acceleration respectively
$\bar{\Sigma}_p$, $\dot{\bar{\Sigma}}_p$, $\ddot{\bar{\Sigma}}_p$	Aiming reference vector line of sight angle, rate, acceleration
$\bar{A}_T$	Target vector velocity
A_a	Attacker vector velocity
$\bar{s}$ x ( )	Vector cross product of line of sight vector with ( )
$\bar{\epsilon}$, $\dot{\bar{\epsilon}}$	Vector angular error, error rate
p, q, r	body axis pitch, roll, yaw angular rates
Φ, ϕ	Inertial pitch, roll angles
$\Delta\phi$	Incremental roll attitude
α_w	Wing angle of attack
Θ_{gL}	Gun elevation above wing zero lift axis
α_q	Gun angle of attack $q = \alpha_w + \Phi qL$
$\dot{\psi}_\beta$	Inertial gun traverse rate across initial
U	Aircraft speed
s	Laplace transform variable
g	Gravity coefficient 32.2 ft/sec^2 = 9.81 meters/sec^2
a_N	Total aircraft left acceleration (lift/mass)
δ_A	Aileron (or differential tail) surface deflection
δ_R	Rudder deflection
L_δ, Lp, Lr, L_β, etc	Aerodynamic dimensional rolling moment coefficients
N , Np, Nr, N_β, etc	Aerodynamic dimensional yawing moment co-efficients
Y_β	Sideforce coefficient
Z_α	Lift coefficient with angle of attack (inverse path time constant)
Mq, M_α, M_δ, etc	Aerodynamic dimensional pitching moment coefficients
T_f	Gun sight sensi (bullet time of flight to target)
V_M	Muzzle velocity of bullet
β	Sideslip angle
Ay	Lateral acceleration

IMPLEMENTATION OF TASK-ORIENTED CONTROL LAWS

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SUMMARY

The implementation of control laws can be considered as a certain phase of the control system development, where the system environment around the control law has to be taken into account with respect to the specific system mission. A number of implications on the control law are typical for this development phase. Those, caused by design aspects, choice of components and the external atmospheric environment are discussed in this paper.

1. INTRODUCTION

The implementation of control laws requires that a great number of aspects be considered during the development process from the earliest control law design to the last flight test evaluation stage in the completed over all system. Of course, there are the simulation and flight test methods which must be designed for specific task oriented systems. However, in particular there are the numerous implications on the control laws resulting from the task oriented specifications and system concept requirements. These lead to repeated redesign along with flight simulation and airborne tests from one development stage to the next. The control law design, particularly for task oriented control systems, cannot be carried out independently from the conceptually necessary or desirable system properties. As fig. 1 shows, this is taken into account for the synthesis procedure by completing the system step by step within the design process using a rather sophisticated facility (ref. 4). The set-up in fig. 1, for instance, combines the more or less automated optimisation procedure with the flight simulation and the control system to be investigated. Real control system hardware can be introduced in an early stage so that a great number of the implications on the control laws can be accounted for before the first test flight. These implications and their effect will be mainly considered in the following, concentrating on those most likely not to be covered elsewhere in this lecture course.

2. IMPLICATIONS FROM SYSTEM DESIGN ASPECTS

Most of the implications are caused by the hardware components which have been chosen for the control system because of certain conceptual task dependent reasons and system structure decisions. For many control system tasks the safety concept is one of the main guidelines for the choice of hardware equipment to be implemented. Availability and cost are other important factors. There are four main groups of equipment which are specified by the conceptual guidelines, the sensor equipment, the actuation systems, the electronic signal processing and the components for the pilot interfacing. Many of these components are definitely specified later in the course of the development, such that their implications on the control laws are usually not taken into account for many cases in advance. Control laws, already optimised for the component equipment, as known at an early stage of development, have to be reviewed with regard to the specific properties of the actual equipment. This is shown markedly by comparison of fig. 2 and 3. Here the effect on an optimised flight path control system by the introduction of sensor signal changes, i.e. derivation of rate of pitch from a pitch attitude gyro signal by digital differentiation and quantisation of the incidence angle signal with 0.2° steps, is dramatic.

Also the system structure can change several times during the entire development process, e.g. in order to get the most efficient solution to comply with the safety requirements. In the following some typical system structures with emphasis on the sensor part and the actuation system are outlined with respect to their implication on the control laws. The signal processing part of the system is not considered to be that significant in its possible adverse implications except for computer capacity constraints when a large amount of sophisticated software is envisioned (Kalman filters, adaptive control etc.). Also the pilot interfaces will only be covered briefly because of more extensive treatment in one of the following lectures.

2.1 THE SENSOR EQUIPMENT

2.1.1 EXTENSION OF THE CONTROL LAW FOR IMPLEMENTATION REASONS

The environment in which the control is embedded, as sensors, actuators and the system configuration, reaffects the control law. Both an extension of the control law algorithm or a modification of the control law parameters and control law structure may be necessary. The extension of the control law caused by configurational aspects of the sensor part of the system, are discussed in this chapter. These aspects can be for instance sensor accuracy (Kalman filtering etc.) or minimisation of sensor hardware, considering control law tasks which demand redundancy. The latter aspect is pursued in the following.

There are many different concepts for redundancy management of the sensors which essentially do not affect the control law algorithm. But for the purpose of reducing sensor hardware filter and observer techniques can be used which lead to algorithms to be supplemented in the control law. Fig. 4 gives an example of a control system using an observer for hardware reduction purposes [5], for instance, for the task of flight path control. There the equations of the aircraft dynamics

$$(1) \qquad \dot{\underline{x}} = \underline{A}\,\underline{x} + \underline{B}\,\underline{u}$$

$$\underline{y}_{MIN} = \underline{C}_{MIN} \cdot \underline{x}$$

$$\underline{y}_{AVAIL} = \underline{C}_{AVAIL} \cdot \underline{x}$$

the observer equations

$$(2) \qquad \dot{\hat{\underline{x}}} = (\underline{A}' - \underline{H}\,\underline{C}_{MIN})\,\hat{\underline{x}} + \underline{B}'\,\underline{u}$$

$$\hat{\underline{y}}_{COMPL} = \underline{C}_{COMPL} \cdot \hat{\underline{x}}$$

and the overall system equations are:

$$(3) \qquad \dot{\underline{x}} = \underline{A}\,\underline{x} - \underline{B}\,\underline{R}\,\hat{\underline{y}}$$

$$\hat{\underline{y}} = \underline{y}_{AVAIL} + \hat{\underline{y}}_{COMPL} = \underline{C}_{AVAIL}\,\underline{x} + \underline{C}_{COMPL}\,\hat{\underline{x}}\ ,$$

where

$$(4) \qquad \underline{C}_{AVAIL} + \underline{C}_{COMPL} = \underline{C}_{NOMINAL}$$

$\underline{A}$, $\underline{B}$, $\underline{H}$, $\underline{A}'$, $\underline{B}'$, $\underline{C}_{MIN}$, $\underline{C}_{AVAIL}$, $\underline{C}_{COMPL}$ and $\underline{R}$ are real constant matrices.

The vector $\underline{y}_{MIN}$ in equ. (1) represents the measurements of a minimal system of most reliable sensors, such that the aircraft motion becomes observable. The sensors, being redundant, represent the minimal amount of sensor hardware on which the system survival calculations can be based. In addition to these sensors, other sensing devices are used to complete the feedback vector $\underline{y}$. These additional sensors may be duplicated and monitored. The sensor monitor controls $\underline{C}_{AVAIL}$ and $\underline{C}_{COMPL}$ in case of failures. The failed sensor signal will be replaced by the corresponding observer output. Of course, $\underline{C}_{MIN}$ is included in $\underline{C}_{AVAIL}$.

With this configuration, observer outputs are only involved in the control loop in case of a failure in the additional sensors corresponding to $\underline{C}_{AVAIL}$. The advantage is that changes of the aircraft parameters due to changes in the operational status are eliminated in the nominal case, which lead to observer inaccuracies ($\underline{A} \neq \underline{A}'$). The same is true with respect to undesired effects of disturbances on the observer.

Other configurations are possible, for instance with the observer being continuously part of the aircraft control loop. In this case the observer is also used for failure detection purposes, but there is observer redundancy demanded. The redundant observer signals can ensure that no failure detection problems arise because of adverse effects of disturbances and parameter changes of the aircraft. However, there are degrading effects on the flight control performance, if these signals are also used for the aircraft control loop. The parameter changes can be taken into account by adaptive use of different parameter settings for the observer, if further extension of the control law can be tolerated with respect to computational effort.

2.1.2 MODIFICATION OF THE CONTROL LAW FOR IMPLEMENTATION REASONS

If the degration resulting from these effects is not acceptable for the case of a sensor failure event with respect to the specific task, not only an extension of the control law algorithm but a modification of the control law structure becomes necessary. A new optimisation run subject to a cost function which takes into account these demands has to be carried out. Fig. 5 shows an example [5] of soft degradation encountered in a specific system due to certain parameter changes (imperfect modelling). However, parameter changes can easily lead to observer instability. The influence of the disturbances and parameter variations on the aircraft output $\underline{y}$, using an observer corresponding to fig. 4, can be described by the following equations (s.ref.1). Denoting $\tilde{\underline{x}}$ by

$$(5) \qquad \tilde{\underline{x}} = \underline{x} - \hat{\underline{x}}\ .$$

The aircraft/observer/control differential equations are

$$(6) \qquad \dot{\tilde{\underline{x}}} = \{\underline{A}' + (\underline{B} - \underline{B}')\,\underline{R} - \underline{H}\,\underline{C}_{MIN}\}\,\tilde{\underline{x}} + \{(\underline{A} - \underline{A}') - (\underline{B} - \underline{B}')\,\underline{R}\}\,\underline{x} + \underline{z}$$

$$\dot{\underline{x}} = (\underline{A} - \underline{B}\,\underline{R}\,\underline{C}_{NOMINAL})\,\underline{x} + \underline{B}\,\underline{R}\,\underline{C}_{NOMINAL}\,\tilde{\underline{x}} + \underline{z}$$

or with $\underline{x}(0) = \tilde{\underline{x}}(0) = 0$ and transforming equ. (6) in the Laplace regime

$$(7) \qquad \underline{y} = \underline{C}_{NOMINAL} \cdot \underline{x} \quad \text{with}$$

$$(8) \qquad \underline{x} = \{\underline{I}s - \underline{A} + \underline{B}\,\underline{R}\,\underline{C}_{NOMINAL}(\underline{I} - (\underline{I}s - \underline{A}' + \underline{H}\,\underline{C}_{MIN} - (\underline{B} - \underline{B}')\,\underline{R})^{-1}[(\underline{A} - \underline{A}') - (\underline{B} - \underline{B}')\,\underline{R}])\}^{-1} \cdot$$

$$\cdot\ \{\underline{I} + \underline{B}\,\underline{R}\,\underline{C}_{NOMINAL}(\underline{I}s - \underline{A}' + \underline{H}\,\underline{C}_{MIN} - (\underline{B} - \underline{B}')\underline{R})^{-1}\}\,\underline{z}\ .$$

As can be seen from (7) and (8), both $\underline{H}$ and $\underline{R}$ are acting on $\underline{y}$ and the cost function used consecutively for the overall optimisation has to include the trade off between the control quality (disturbance response) and the observer behaviour. A new control law will be generated.

A very simple observer design for reducing the amount of sensor hardware, which has to be accounted for with respect to the performance (magnitude) in system reliability, is that of simple integration in the observer. Fig. 6 shows the block diagram of a helicopter flight path demand control system. This system has two operating modes, the <u>nominal</u> one which uses all possible sensor informations for a velocity demand control and the <u>minimal</u> operating mode, where only accelerometers and gyros but neither velocity sensors nor sensing

devices for the aerodynamic status are available (ref.6). The latter mode essentially provides an acceleration demand control. In order to achieve acceleration control without stationary derivations double integration would be necessary in the control loop. However, since

1) a change in velocity instead of acceleration is what is really controlled by that acceleration demand control (this mode can only be operated by impulsive type inputs) and

2) the nominal mode control loop can achieve stationary velocity control without control error by using velocity sensing devices and one integration only in the control loop

the second integrator could be omitted.

In that case the original control law for the task of flight path control which provides good performance when operating in the nominal mode, has to be modified (s.fig. 6) in order to achieve sufficient control performance (incl. decoupling) and to comply with the structure of the minimal system. In the case of this helicopter program (s.fig. 7), which is conducted by Dornier, no single main control law was required. New control parameters were activated when switching from one mode to the other. The main control loop structure remains unchanged, though.

2.2 ACTUATORS AND CONTROLS

Depending on the mission and the mission survival specifications also different concepts for the controls and actuation systems are to be considered.

On one hand the conventional number of controls could be used, perhaps including DLC and direct side force control surfaces. If these basic control surfaces are driven by analog actuation systems (e.g. triplex or duo duplex) no major impacts on the control laws are usually to be expected, although many well known problems are related to this concept. Only specific nonlinearities of the mechanical linkage between actuator and control element and dead zone behaviour may cause more severe changes in certain systems (s. fig. 7 'Nonlinearities of Throttle Actuation in HFB 320 and Optimisation Run'). Fig. 7 also shows how it can be compensated for known backlash and hysteresis effects by control algorithm changes (ref.3). More difficulty arises if these nonlinearity characteristics vary considerably during flight (e.g. because of temperature changes).

On the other hand concepts of multitudinous split control surfaces are considered, as possibly used for certain mission oriented aircraft. These are independently driven by the control law for reasons such as reduction of vulnerability and actuator hardware (using simplex actuators because of the control surface redundancy) and better control capability for aeroelastic modes. Assuming that the failure detection can also be a simple monitoring feed back, in this case the servo control loop for the control surface positioning using a discrete actuator input, might be only necessary as a secondarily working loop and might be build up by the aircraft outer control loop itself.

Fig. 9 shows the principle loop structure and fig. 10 shows the failure transients of the lateral aircraft motion (HFB 320, 150 Kts) due to an aileron drift rate of 0,5 (o/s), when no drift sensing device and no additional counteraction is applied. In this case the aircraft control loop consists of a bank angle command control and lateral stabilisation loops. In essence, the stationary effect of the aileron drift rate results in a failure behaviour equivalent to a bank angle command bias. That means, as long as the control law does not fail, this kind of drift failure does not lead to a critical aircraft motion. The control law used for this simulation trial was determined without taking this kind of actuation failure into account. Thus, further improvements are possible, when this aspect is covered by the cost function. For instance, the value of the integrator coefficient $K_{\xi\int\phi}$ directly influences the stationary bank angle deviation. Furthermore drift compensation can be achieved on the computational basis without additional feedback. The observer estimates for the aircraft state can be used for drift detection.

2.3 PILOT INTERFACES

When the pilot is involved in the control loop, e.g. by pilot command control in flight tasks like flight path control, certain manoeuvre flight, also the pilot and the flight instrumentation become an important part of the environment to which the control law has to be adjusted along with its implementation. The flight director law of the manual control can be considered as the simplest version of the control law for a flight path command control task (s. fig. 11). The remaining configurations on fig. 11 show three alternatives for longitudinal command control, $\dot{\Theta}$-,$\dot{\gamma}$- and γ-command where both the flight director law and the main control law have to be considered. For the two latter command versions, the control law design can be carried out separately for the flight director and the automatic controller. No major adjustment changes are to be expected after flight simulator testing for reasons of pilot-in-the-loop-control. Furthermore these configurations show better flight path tracking performance compared to the $\dot{\Theta}$-command. This was found during a flight simulator study for a statistical evaluation of the flight path tracking accuracy of the four versions shown in fig. 11. Fig. 12 shows the statistical results in terms of the means of standard deviations of relevant flight path parameters subject to a curved steep approach flight path profile (ref. 8).

The mean value of the standard deviations and the scatter around this value, again expressed as standard deviation, are plotted for the deviations in height, speed and bank angle. Two kinds of columns are shown in the case of 'γ-command'. Those drawn with dotted lines illustrate the results for a pure γ-command configuration. The solid line columns show the results for γ-command with artificial lag of the pilot signal with a time constant of 5 seconds. The results appear to be almost identical to those of the $\dot{\gamma}$-command case.

In spite of these results also the $\dot{\Theta}$-command might be preferable for certain tasks when attitude control (pointing) is equally important compared to flight path control. In this case the adverse interactions between pilot loop (FD-law) and automatic flight control are to be minimised by flight simulator evaluations as well as flight test. These interactions are mainly caused by the simultaneous feed back of the disturbed

control quantities to the pilot and the automatic controller. Additional means as open loop gust and wind shear alleviation can be introduced for this purpose as will be treated in the following section.

3. EXTERNAL DISTURBANCES

External disturbances only cause the interactions between pilot control and automatic control. Furthermore, the control law for the automatic controller itself of a flight path control system usually must be a compromise with respect to certain requirements when the effect of external disturbances is concerned. As a typical example a STOL approach simulation for a DO 28 (longitudinal motion) is shown in fig. 13 with an integrated flight control system developed by the Bodenseewerk. This automatic control system controls the flight path via the height and the aerodynamic state via the angle of attack. The throttle and elevator are used as controls. Fig. 13 illustrates two approaches under same external conditions using this flight control system. The coefficients of the control law were modified according to different requirements. For the first case the coefficients were defined by a cost function weighting with particular regard to low throttle activity. Fig. 13 shows that this results in a larger flight path deviation. This deviation occurs typically under the effect of stronger wind shear. The wind shear of the magnitude of about 7 ats/100 ft is encountered by the aircraft in the height interval 300 m<h<400 m. For the second approach the coefficients of the control law were defined with particular regard to the flight path guidance accuracy. Here higher throttle activity was permitted in favour of more efficient counteracting against the disturbances.

A technique other than feed back control has been tried in order to eliminate external disturbances such as gusts and wind shear. That is the open-loop compensation of external disturbances. In this case the implementation of a flight path guidance control law does include a superposed open loop control derived from direct measurement of the disturbances. An immediate control reaction with respect to a disturbance can be achieved as opposed to the feed back control where integral behaviour and moderate feed back amplification (for stability reasons) cause substantial loss in effective compensation.

Despite this fact, so far no really encouraging experimental data is known because of two main difficulties,

- the measurement problem and
- the insufficient dynamic and stationary properties of the control elements.

Much activity has begun on these issues using modern filtering techniques and unconventional control elements in order to achieve disturbance measurement information of sufficient accuracy and better control element capabilities respectively.

In the following a specific open loop control law for the longitudinal motion which has been derived in ref. 7 from the following set of nonlinear equations, will be stated describing the longitudinal motion:

$$\begin{pmatrix} m\dot{V}_K \\ -m\dot{\gamma}V_K \\ I_y\,\dot{q} \\ \dot{\Theta} \end{pmatrix} = \begin{pmatrix} -D+L\cdot\alpha \\ -L-D\cdot\alpha \\ M_A \\ q \end{pmatrix} + \begin{pmatrix} -\Theta \\ 1 \\ 0 \\ 0 \end{pmatrix} W + \begin{pmatrix} 1 \\ -\alpha \\ z_T \\ 0 \end{pmatrix} T \tag{9}$$

$$\begin{pmatrix} \dot{u}_w \\ \dot{w}_w \end{pmatrix}_g = \begin{pmatrix} u_{wx} & u_{wz} \\ w_{wx} & w_{wz} \end{pmatrix}_g \cdot \begin{pmatrix} 1 \\ -\gamma \end{pmatrix} V_K \tag{10}$$

$$\begin{pmatrix} 1 \\ -\gamma_a \end{pmatrix} V = \begin{pmatrix} 1 \\ -\gamma \end{pmatrix} V_K - \begin{pmatrix} u_w \\ w_w \end{pmatrix}_g \tag{11}$$

and

$$\Theta = \gamma + \alpha + \alpha_w = \gamma + \alpha + \frac{u_{w_g}}{V} + \frac{w_{w_g}}{V} \tag{12}$$

The geometrical relationships of (11) and (12) are derived from fig. 14. There

u_{w_g} = wind component in the geodetic x-axis

w_{w_g} = wind component in the geodetic z-axis

$u_{wx} = \frac{\delta u_w}{\delta x}$, etc.

V_K = speed of the aircraft relative to the earth

V = speed of the aircraft relative to the surrounding air

V_w = wind velocity relative to the earth

The remaining denotions from (9) and (10) are commonly used in the literature and are considered here as well known. There are three control elements considered to be available for the longitudinal control which are elevator, thrust and flap control. There are only three variables, therefore, which in the ideal case can be protected from the disturbances. These have to be carefully chosen corresponding to the flight task.

Because of the fact, that the low frequency disturbances such as wind shear have the most adverse effect during a specific section of the flight mission, namely the landing approach, different open loop control laws are defined in the high and low frequency region of external wind disturbances.

For the low frequency region, e.g. the landing approach task, the requirements in this case are defined such that the disturbance effects on the airspeed V the flight path angle γ and the angle of attack shall be eliminated. This makes sense during the approach phase, when the aircraft shall be kept unaffected in its aerodynamic status and on its flight on the glide path:

(13) $\dot{V} = \dot{\gamma} = \dot{\alpha} = 0$

From equations (9) through (12) then a control law approximation ($L \approx W$) can be derived [7]:

(14)

thrust control: $\frac{\Delta T}{W} = \frac{\Delta u_{w_g}}{V_o} \gamma_0 + \frac{\Delta w_{w_g}}{V_0} + \frac{\Delta \dot{u}_{w_g}}{g}$

flap control: $\Delta \delta_F = 0$

elevator control: $\Delta \eta = - \frac{C_{Mq}}{C_{M\eta}} \left(\frac{\Delta \dot{u}_{w_g}}{V_0} \gamma_0 + \frac{\Delta \dot{u}_{w_g}}{V_0} \right) - \frac{M_T}{M\eta} \Delta T$

This shows that, in essence, no stationary flap control is demanded and that the thrust control changes in proportion to the derivative of the horizontal wind velocity. Fig. 15 illustrates the change in thrust control as a function of a certain wind profile and the share of each term of the thrust control law for a DO 28 STOL-aircraft.

For the high frequency case flight path and pitch angle changes are considered as most undesired [7] if they result from gust disturbances:

(15) $\dot{V}_K = \dot{\gamma} = \dot{q} = 0$

This results in the following high frequency control law, when keeping the thrust control unused [7]:

(16) $\Delta T = 0$

$$\Delta \delta_F = - \frac{2 C_{DO}}{V_0 \, C_{\Delta \delta_F}} \Delta V - \frac{C_{\Delta\alpha} + C_{DO}}{C_{\Delta \delta_F}} \Delta\alpha$$

$$\Delta \eta = - \frac{1}{C_{M\eta}} \left\{ \frac{2}{V_0} C_{MO} \Delta V + C_{M\alpha} \Delta\alpha + C_{M\dot{\alpha}} \Delta\dot{\alpha} + C_{M\delta_F} \Delta\delta_F + K_\Theta \Delta\Theta + K_q \cdot q \right\}$$

It becomes evident, that this control law is no longer representing an open loop control rather than a feed back control, mainly by ΔV and $\Delta\alpha$. This results in stability changes. From the equation for $\Delta\eta$ it becomes obvious, for instance, that for the sake of no effect of α_w on the pitch moment the static stability is

nulled out by the term $-\frac{C_{M\alpha}}{C_{M\eta}}\Delta\alpha$. Additional "control configuring" feedback terms with $\Delta\Theta$ are necessary (K_Θ and K_q) in order to ensure proper static and dynamic stability margins.

4. CONCLUDING REMARKS

Within the overall control system the control law and its system environment has gained more and more complexity. Many tasks have been included and a great number of requirements are involved with respect to specific missions. An increasing amount of onboard computational capacity has been made available along with the increasing control law complexity. This induces possible modifications of the conventional system structure and because of that also implications on the control laws. Besides the control performance aspect, the system integrity and system simplicity with respect to the hardware effort appear to be some of the main driving factors. Many of these implications are encountered during the control law implementation phase, when hardware layout and control law design are to be tied together.

In this paper several implications on the process of establishing the control law, induced by hardware layout specifications, are described. In addition, the aspect of possible control law enhancement in eliminating external atmospheric disturbances is included.

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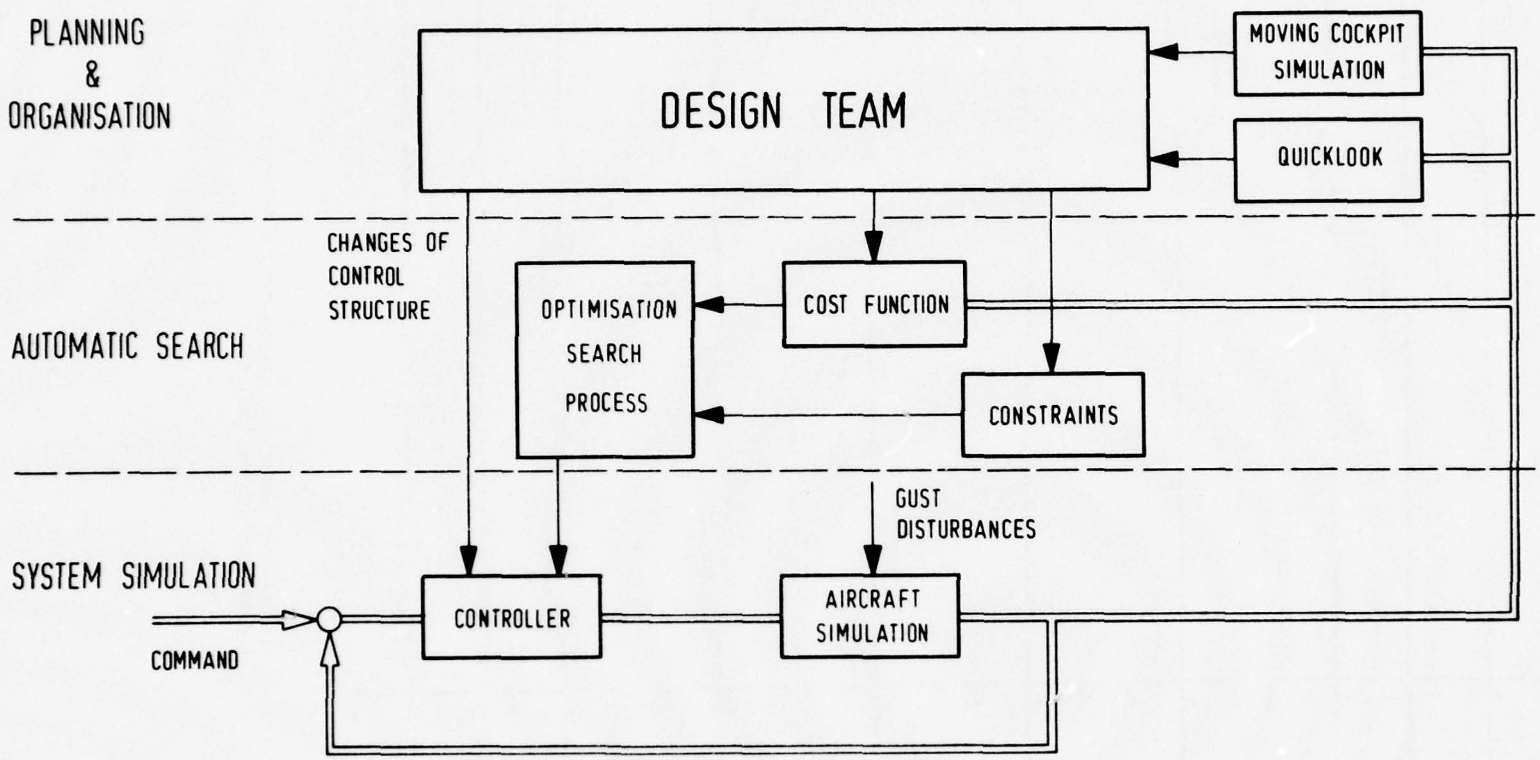

Fig. 1: Simulator aided control law synthesis.

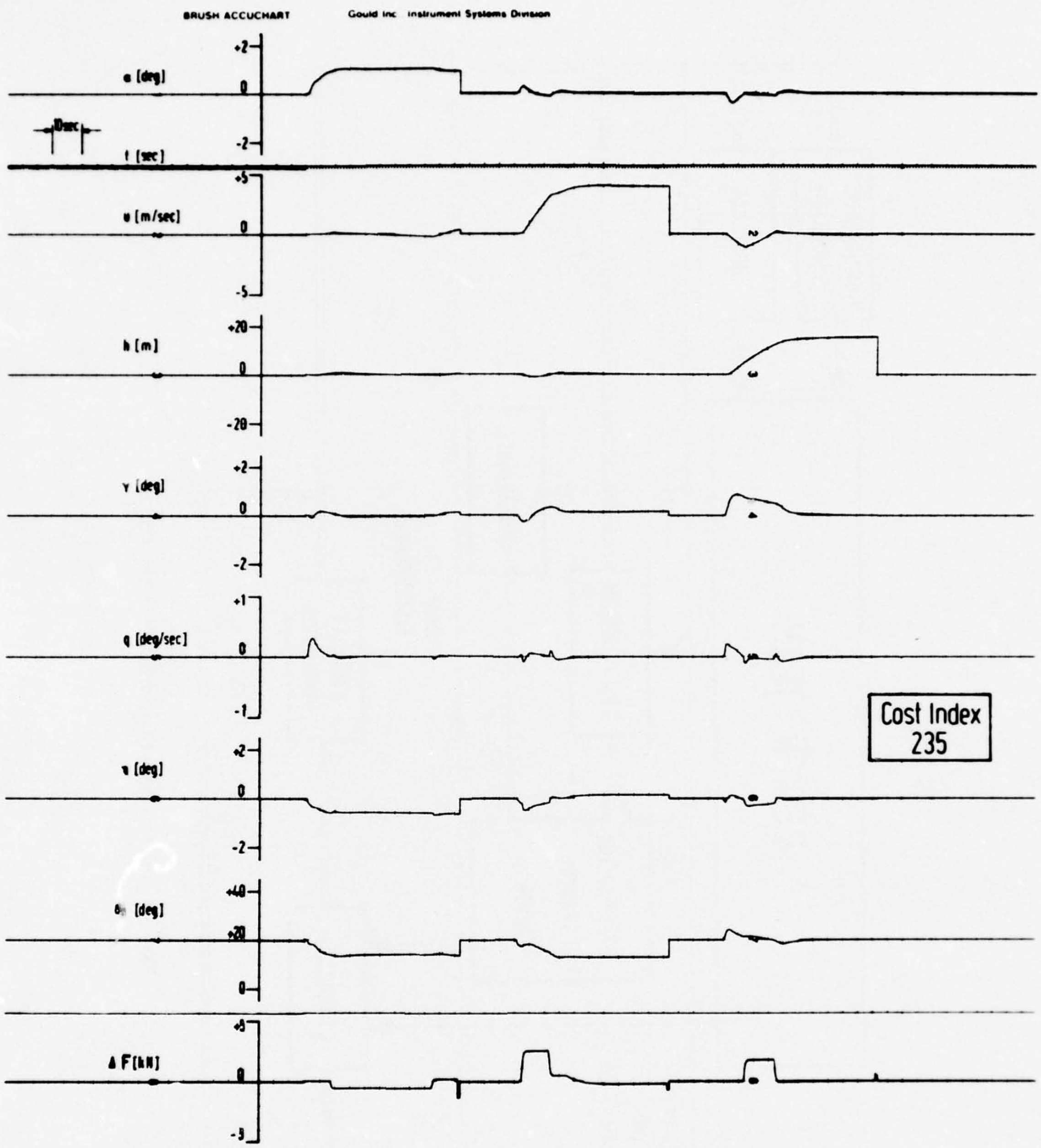

Fig. 2: Optimisation search for command control in height, speed and angle of attack (ref. 4)

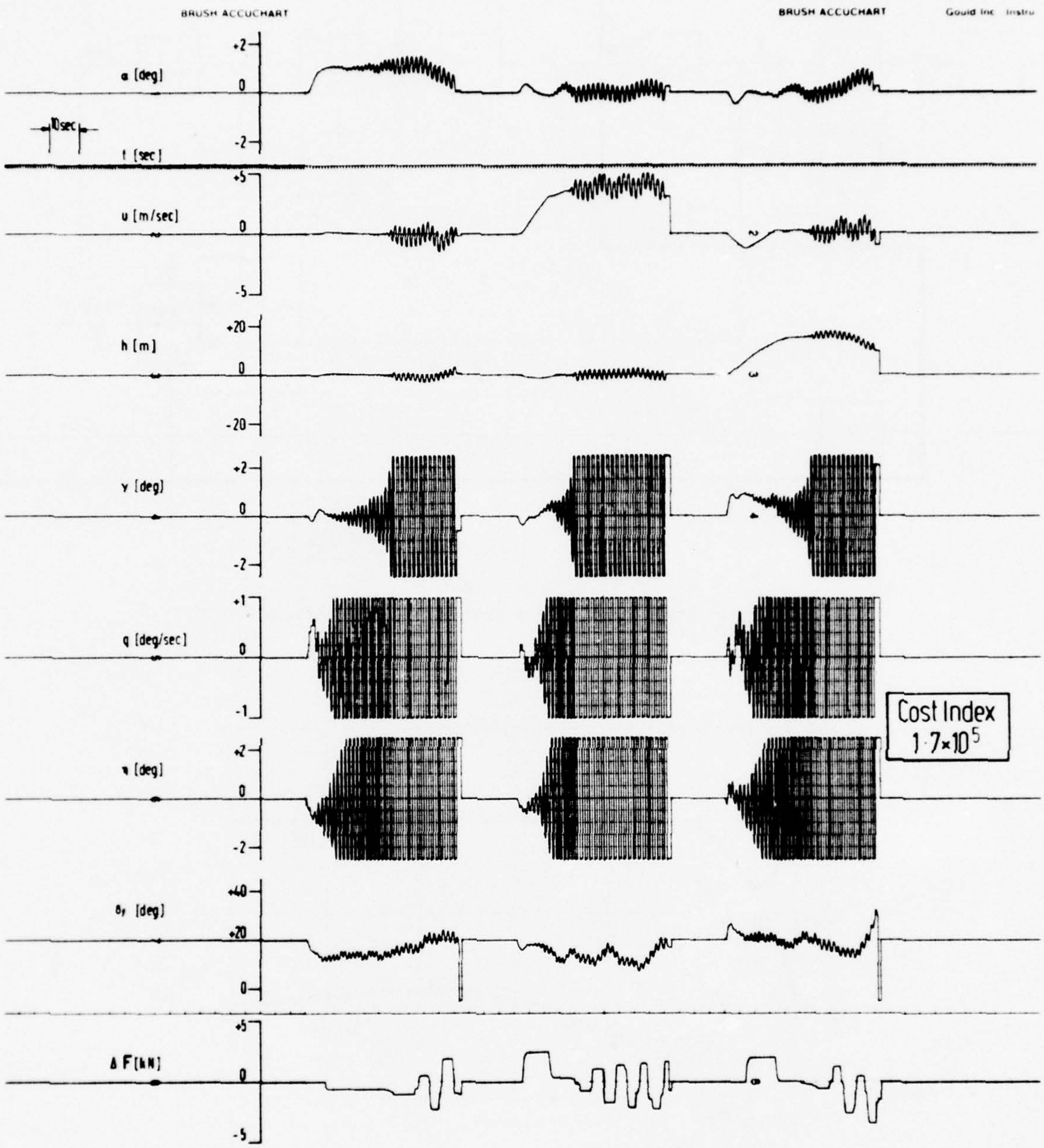

Fig. 3: Optimisation search, introduction of sensor-nonlinearities in simulation resulting from fig. 2 (ref. 4)

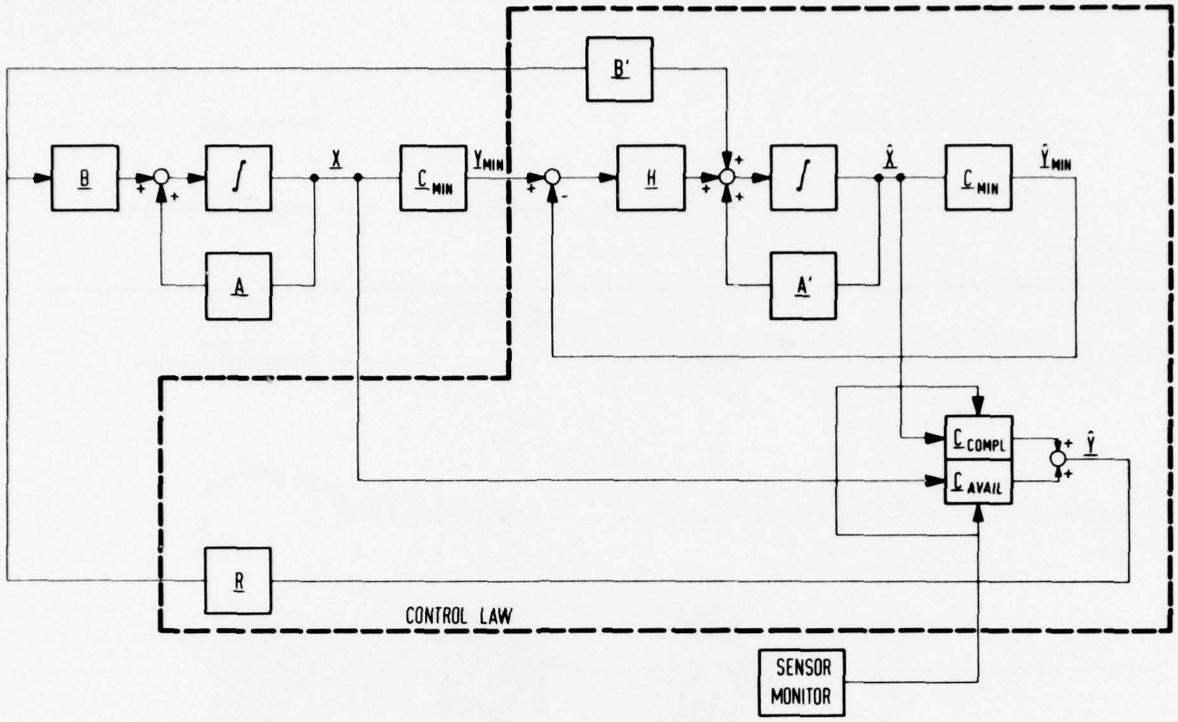

Fig. 4: Observer implementation for redundant signal information of aircraft state

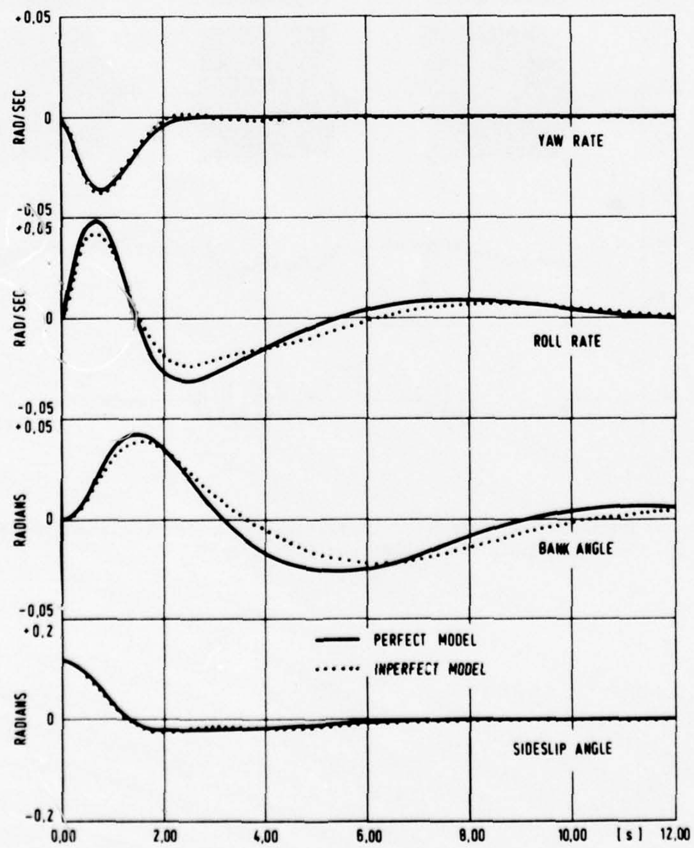

Fig. 5: Signal degradation due to imperfect modelling (moderate) (ref. 5)

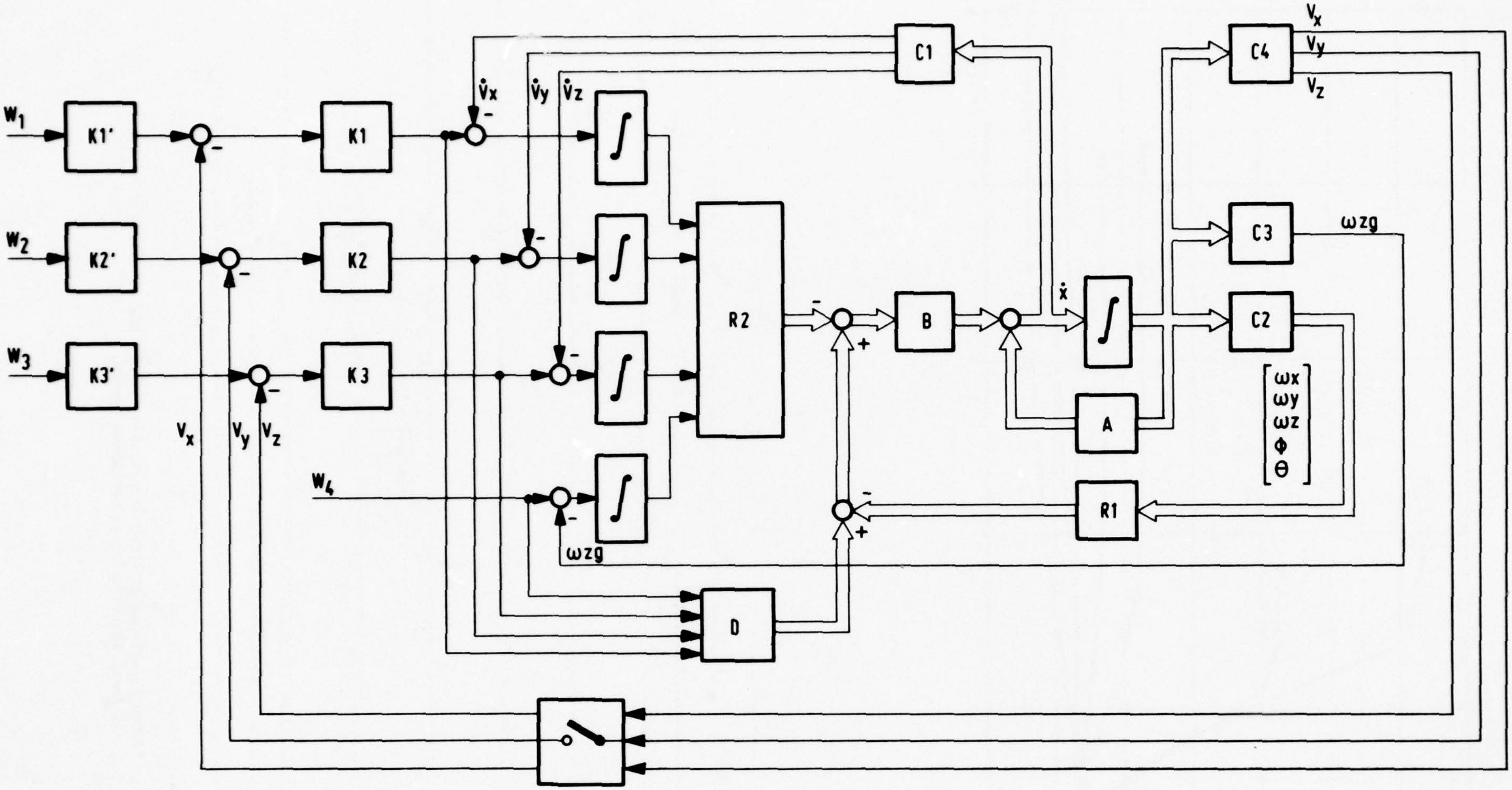

Fig. 6: Demand control system for speed and acceleration.

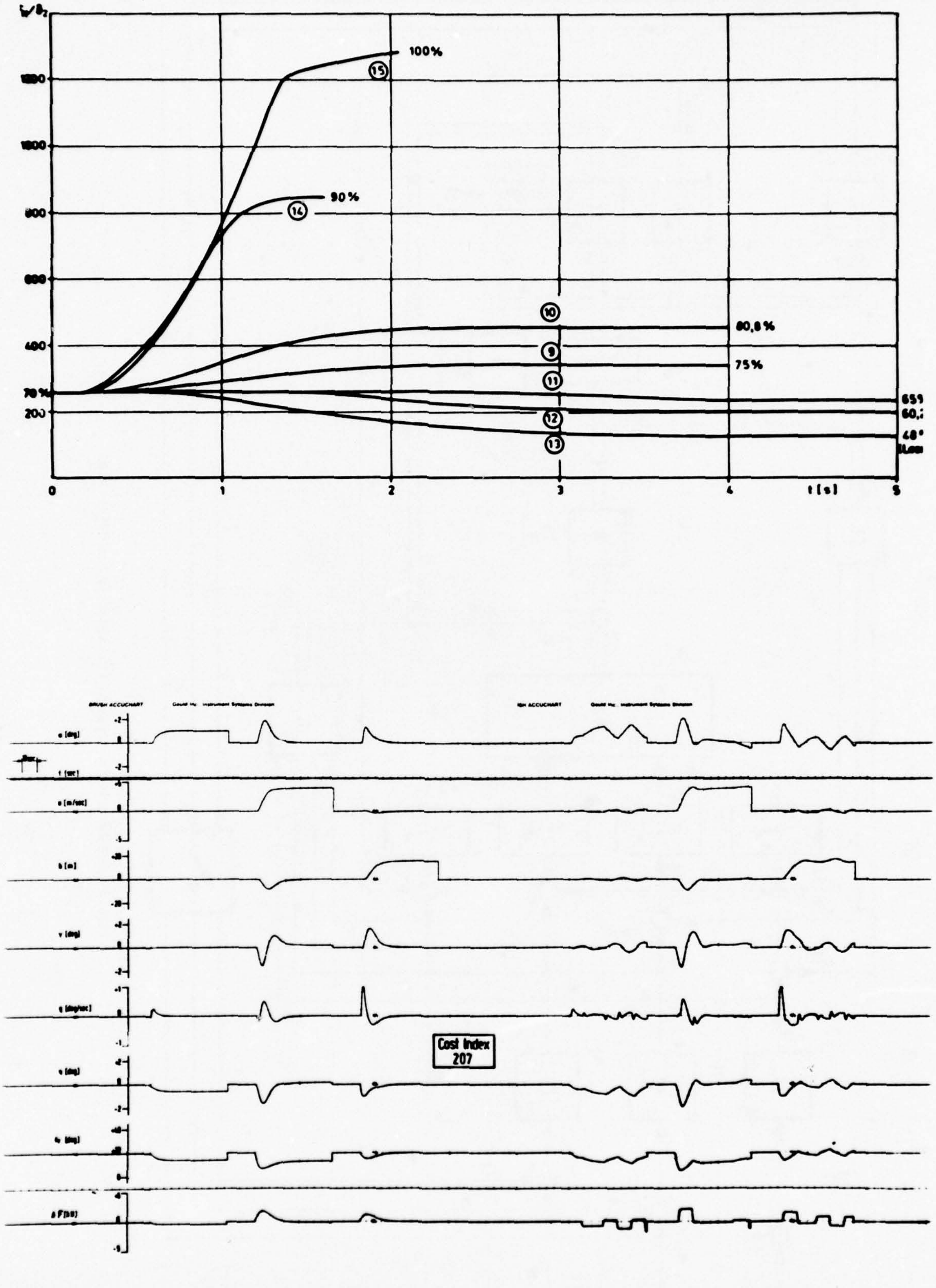

Fig. 7: Nonlinearities of throttle actuation in HFB 320 and simulation results of their introduction in optimised system.

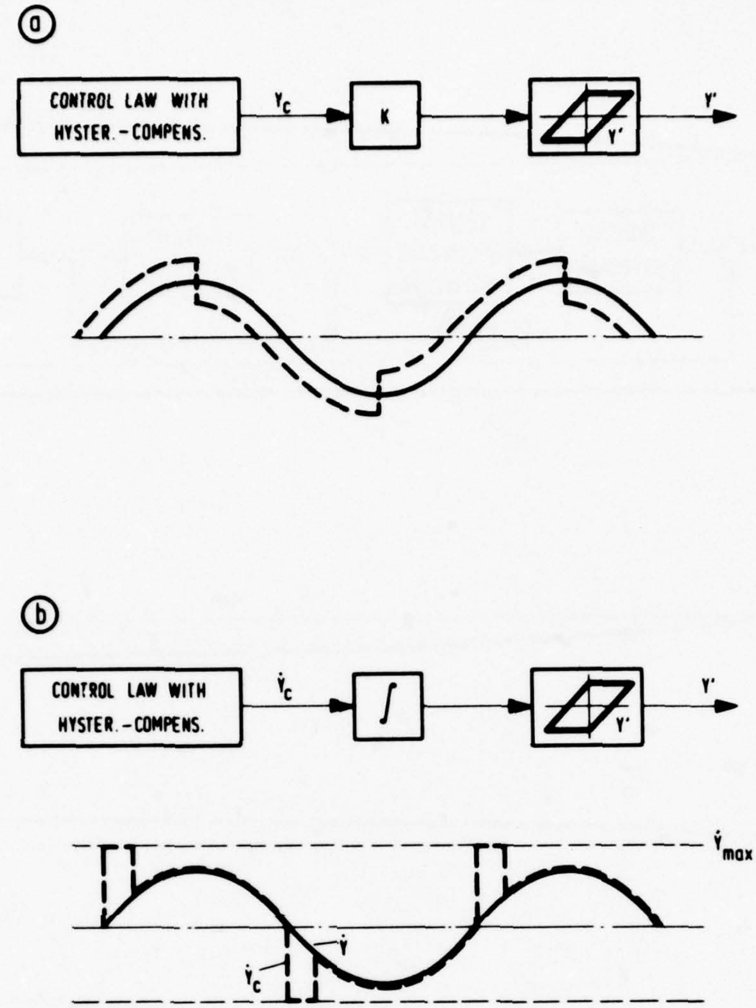

Fig. 8: Hysteresis compensation of control element with a) proportional, b) integral behaviour.

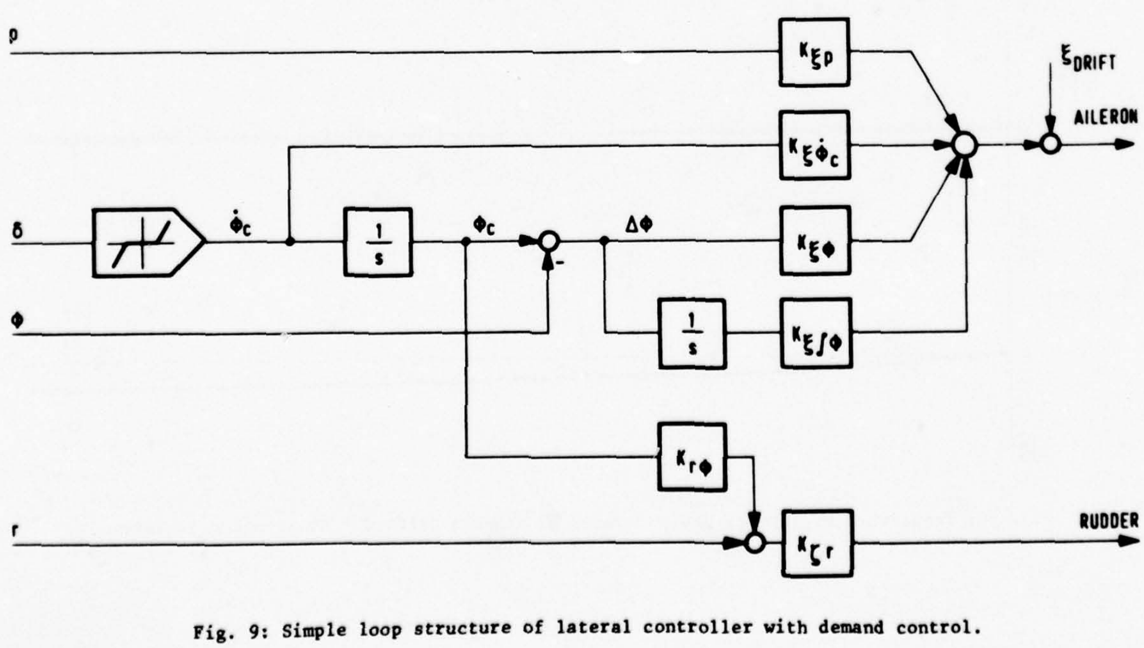

Fig. 9: Simple loop structure of lateral controller with demand control.

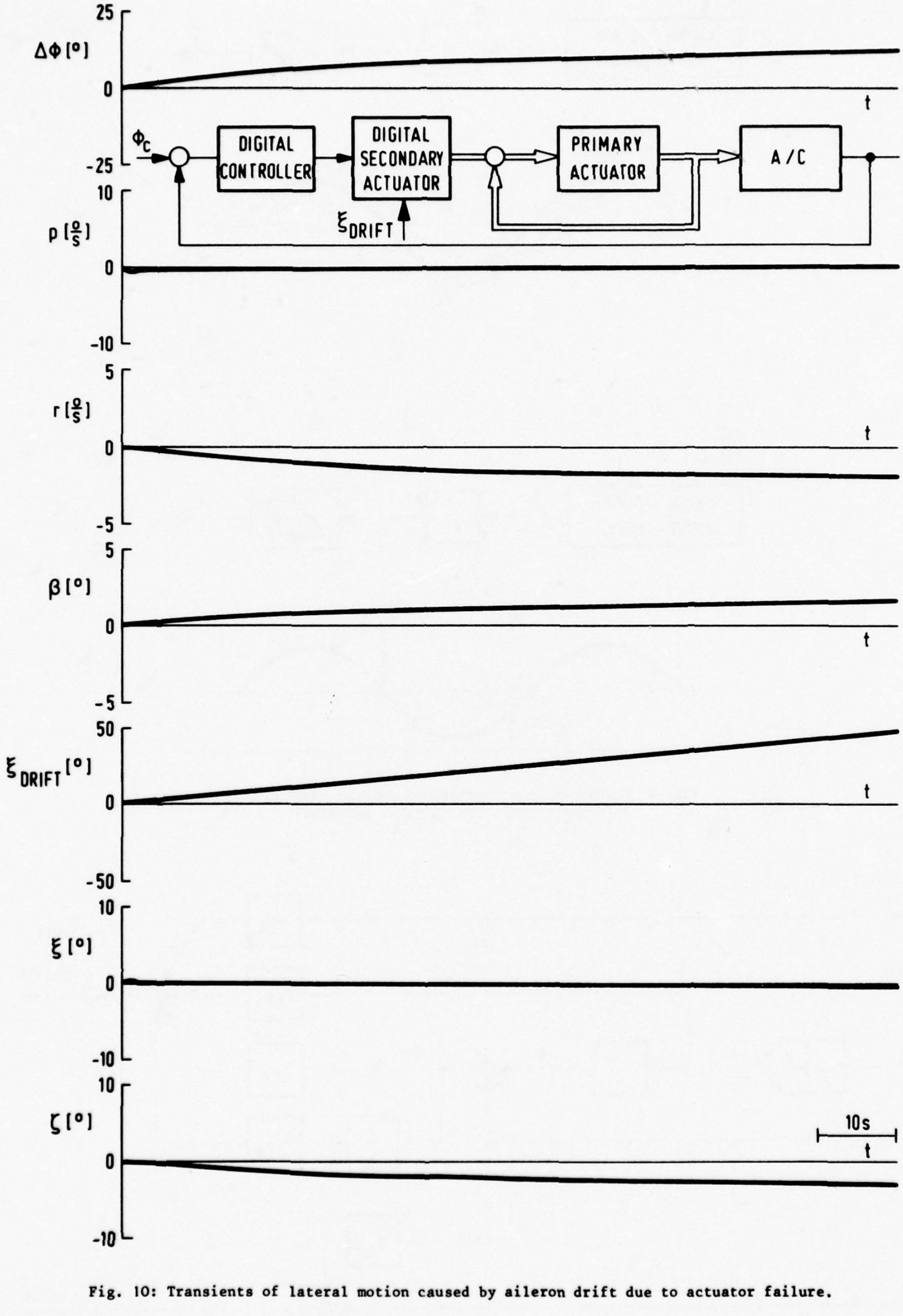

Fig. 10: Transients of lateral motion caused by aileron drift due to actuator failure.

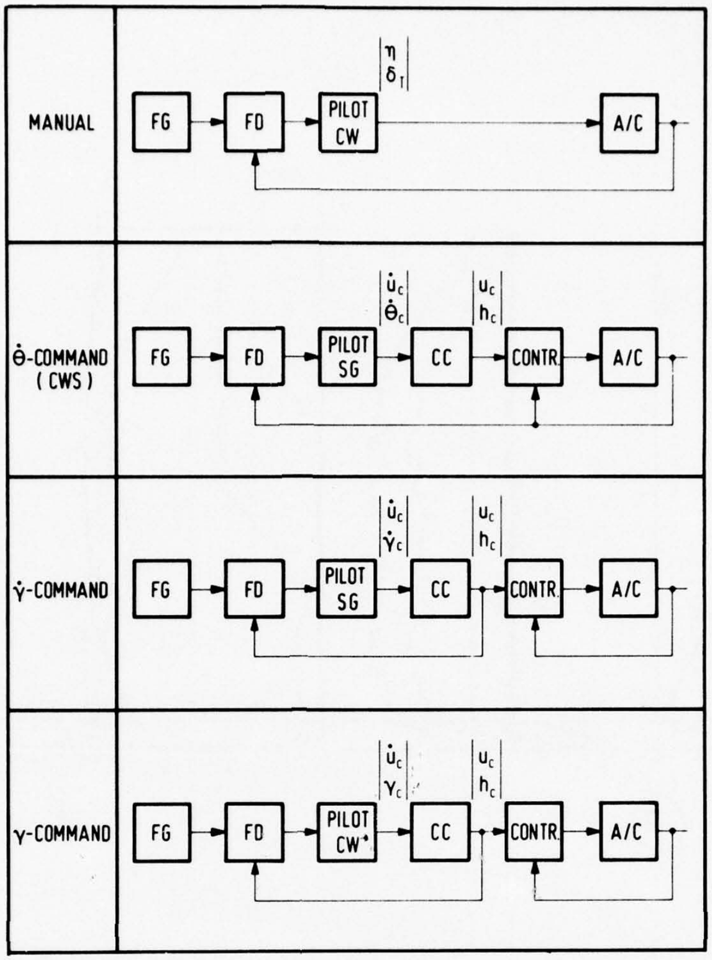

Fig. 11: Configurations of flight path demand control (longitudinal motion) (ref. 8).

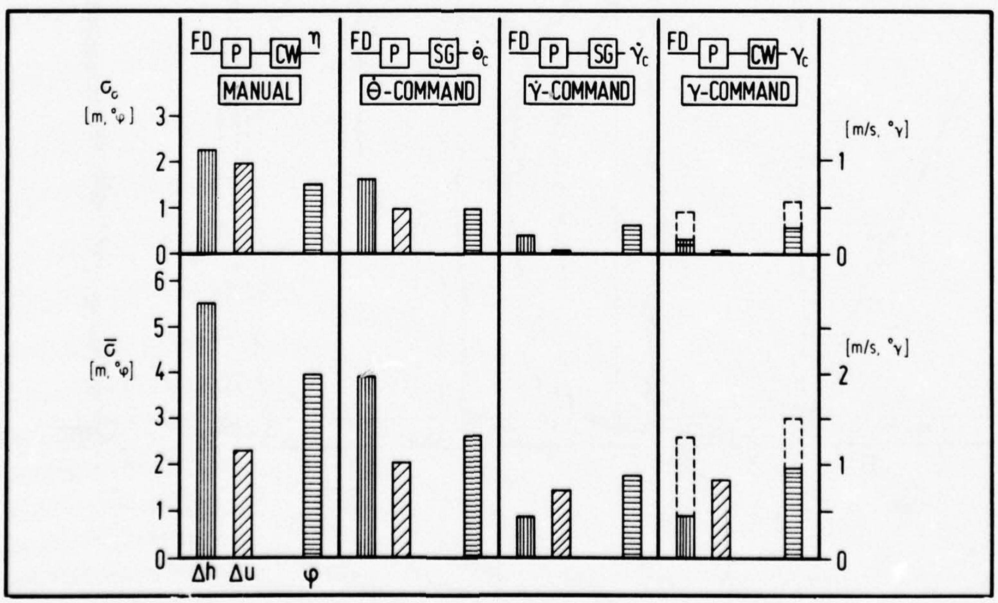

Fig. 12: Statistical results of deviations in flight parameters using the configurations of fig. 11 (ref. 8).

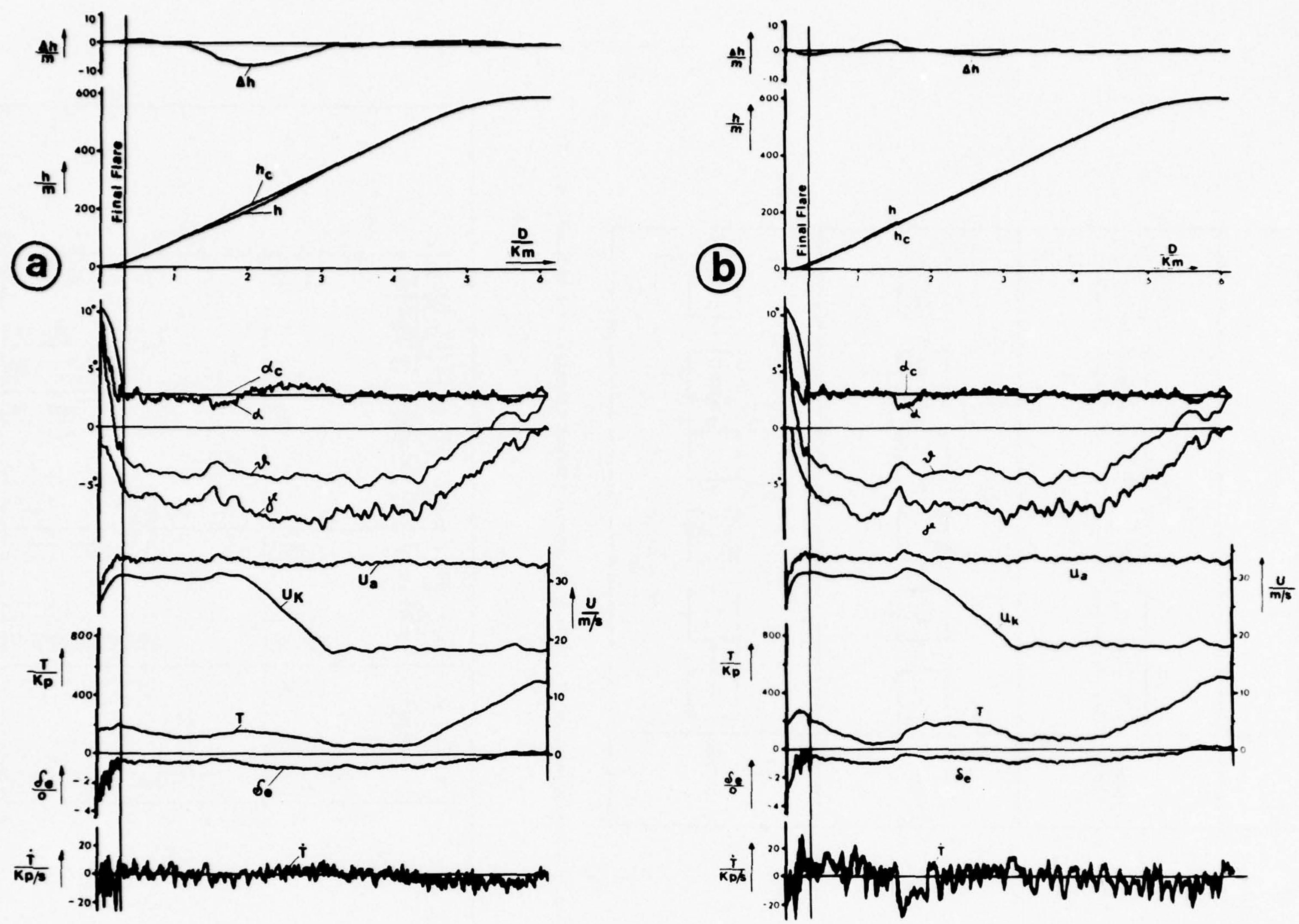

Fig. 13: STOL-Approach of Do 28

a) Height cost function weighting on throttle activity
b) High cost function weighting on flight path deviations (ref. 2).

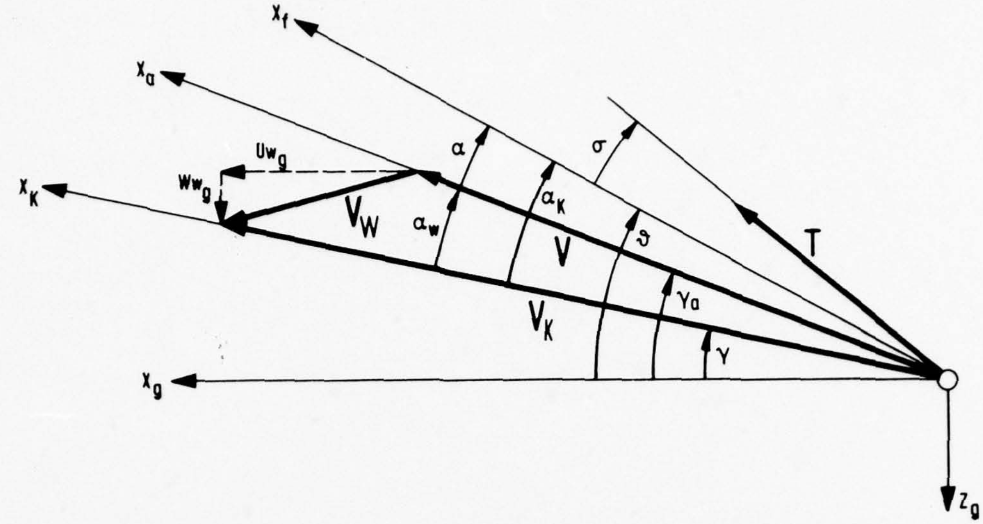

Fig. 14: Flight mechanical denotions of longitudinal parameters, including wind (ref. 7).

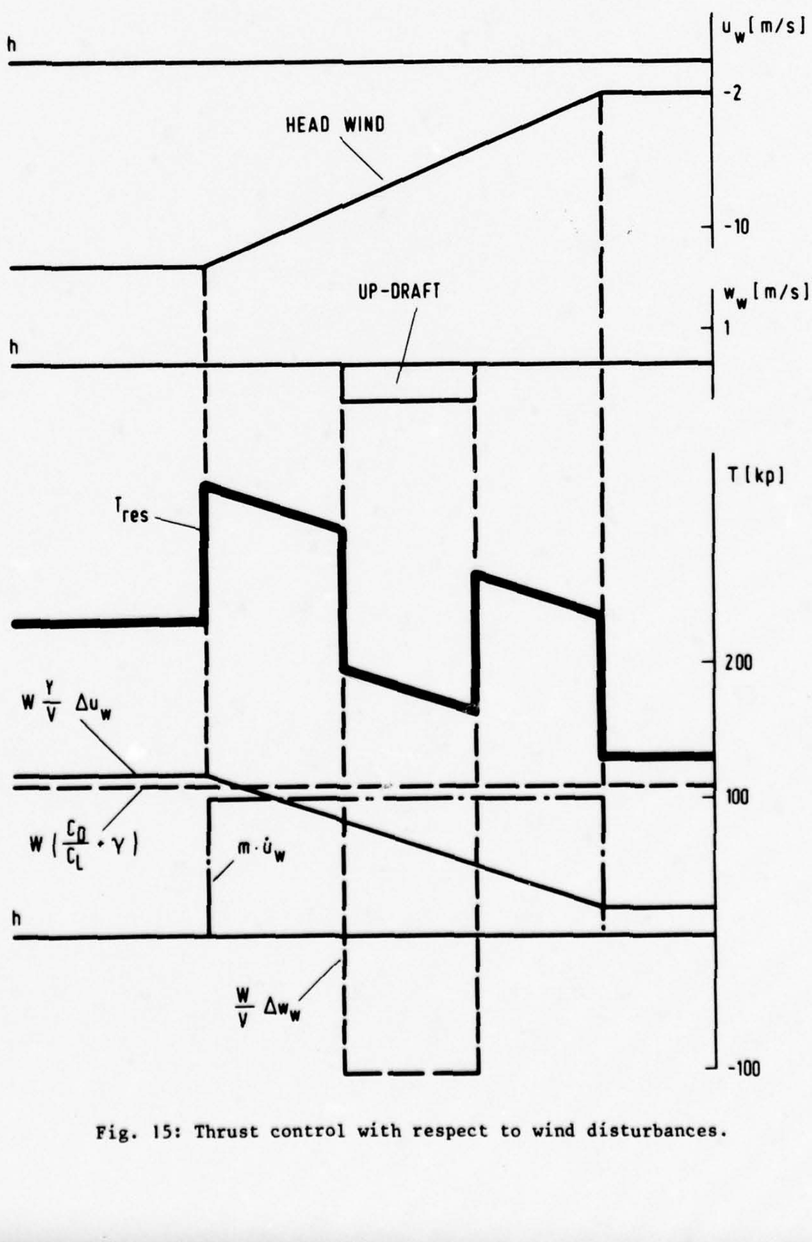

Fig. 15: Thrust control with respect to wind disturbances.

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ADDITIONAL DEGREES OF FREEDOM

by

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ABSTRACT

Additional degrees of freedom consisting of direct lift and direct side force are introduced and associated task oriented flight control system functions are discussed. Direct lift systems which improve the capability of both commercial and conventional fighter aircraft are presented. The impact of a fly-by-wire implementation on the aerodynamic and structural design of a Vectored Lift Fighter concept is discussed. It is shown that these additional degrees of freedom can lead to innovative modes of operation. Maneuver enhancement with direct lift and wings level turning with direct side force are presented. Technical considerations related to vertical and lateral translation and fuselage aiming mode implementations are reviewed. Pilot interface techniques and blended control are introduced. Guidelines for using the additional degrees of freedom are presented.

INTRODUCTION

Advancements in flight control system technology have impacted mission related capabilities throughout the operational flight envelopes of various classes of aircraft. Aircraft stability and handling qualities have been significantly improved by the introduction of high gain, wide bandwidth stability and control augmentation systems. These low authority systems improved frequency and damping through aircraft rotational motion using conventional aerodynamic surfaces (elevator, aileron, and rudder). High authority control augmentation and fly-by-wire flight control systems now being integrated early in the aircraft design cycle, are showing further evolution and impact on mission capabilities[1].

When additional degrees of freedom (Figure 1) and fly-by-wire techniques are incorporated into an aircraft, mission (task) oriented modes of operation can be generated which show promise for performance improvement in a number of applications. In the implementation of these modes, considerations dealing with airframe, the flight control system, and the crew station interface must be addressed in order to achieve an effective design. The overall technology has progressed to the point where incorporation of these additional degrees-of-freedom in the early phases of a new vehicle, as was done during the Vectored Lift Fighter concept development, results in a highly efficient vehicle which is capable of unique flight maneuvers.

In conventional airplanes, pilots normally utilize direct independent aerodynamic control over only four degrees-of-freedom. They can command three axis rotational rates (pitch, roll, yaw) using existing control surfaces but translational control is usually limited to the throttles and speed brakes. There are no dedicated surfaces incorporated for translational control in the normal and lateral directions. With the use of additional degrees of freedom (direct lift and direct side force) however, complete control in six degrees-of-freedom can be achieved, but this requires extra control forces in pitch and yaw.

Depending on the special configuration and the intended use of the vehicle, direct lift and direct side force implementation could theoretically be accomplished with either propulsive forces or with forces generated by aerodynamic control surfaces. Aerodynamic approach being more efficient have received the most attention because potential payoffs can be predicted for both military and commercial aircraft.

The use of auxiliary surfaces such as flaps, slats, and drag petals has enabled demonstrations of limited magnitude of direct lift and direct side force capability as additions to conventional configurations. Recent developments at MacDonnel Aircraft Company (McAir) have shown that the process of designing new aircraft for large amounts of direct lift and direct side force literally shapes the vehicle (Figure 2) and provides greatly improved effectiveness with an inherently simplified design approach. With an aggressive integration approach in the initial configuration design phase, the large number of control surfaces normally used are reduced to just a few, as depicted in Figure 2. A corresponding reduction in system design integration complexity and parts count also results.

Integration of the additional degrees-of-freedom with conventional control requires specific functional capabilities in the flight control system. Control law computational requirements including dynamic shaping, gain scheduling and mode switching are required to ensure that the aircraft control is provided with a stable, rapid response. The system must be reliable so that safety of flight is not compromised. In addition, the feedback sensors, hydraulic actuators, and pilot commands must be efficiently interfaced to permit closed loop control of the aircraft. The use of fly-by-wire control of all control surfaces, or at least of those dedicated for blended control, is an efficient means of satisfying these requirements. The computational flexibility provided by digital flight computers is an added feature of fly-by-wire control which facilitates effective implementation of the added degrees-of-freedom.

Control of the additional degrees-of-freedom requires that the pilot functions be incorporated in a manner which does not adversely affect the pilot workload. Direct lift and direct side force can be integrated so that pilot controls are operated in the conventional manner. This approach implies a coupled blending of the additional degrees-of-freedom without the use of an auxiliary controller. Another approach is to provide independent manual control of the additional degrees-of-freedom with an auxiliary controller in addition to conventional control of the aircraft. Selection of either approach depends on the particular application. Both approaches can be used in the same vehicle because each produces optimum pilot control in certain mission segments.

LONGITUDINAL FLIGHT DYNAMICS

Longitudinal flight dynamics can be represented with small perturbation equations of motion consisting of one pitch moment degree of freedom and one lift force degree of freedom. The two principal differential equations reflecting these longitudinal degrees of freedom are shown in Figure 3 with the associated coefficients for the aircraft motion parameters and the aerodynamic control surface deflections. The coordinate system shown identifies the rotational rates, accelerations, and control surface deflections and indicates the positive value directions. Typically, the moment terms are inversely proportional to the aircraft pitch inertia. Both the moment and lift terms vary directly in proportion to aircraft wing area, dynamic pressure, and nondimensional aerodynamic coefficient. The lift terms are also inversely proportional to aircraft mass and forward velocity. The physical, inertial, and aerodynamic terms as reflected in the coefficients of the equations of motion, determine the dynamic response of the aircraft to control surface inputs.

The moment and lift equations are coupled through the aircraft motion and control surface deflection parameters. The coupling effects are expressed as cross diagonal terms in the equations of motion shown in Figure 3. A completely decoupled airframe is one in which the cross diagonal terms are minimized to approach zero and pure pitch rate is achieved for a moment surface deflection while pure angle-of-attack is generated from a direct lift surface deflection. Complete decoupling is required in some applications and limited degrees of decoupling are used in others. Direct lift control provides an effective capability for generating the required level of decoupling (or coupling) needed for a particular application. By using the flight control system for blending the deflection of direct lift and moment control surfaces, new modes of control can be implemented which show promise for increased effectiveness in various mission segments and operational roles.

DIRECT LIFT CONTROL IN FIGHTER-ATTACK AIRCRAFT

Control of airspeed and flight path angle is required in fighter-attack aircraft for achieving an effective carrier landing capability. Airspeed and flight path angle control can be implemented in many different ways depending on the type of vehicle and the desired mix of manual and automatic control. Extensive design efforts are sometimes required for generating an acceptable configuration. Direct lift control has been investigated for use during carrier landing and is presented in the form of simplified examples to illustrate possible applications of this concept.

During carrier landing, fighter-attack aircraft operate at low approach speeds and elevated angles-of-attack. These characteristics and associated flight path stability considerations may indicate a need to maintain constant angle-of-attack to ensure safe operation in the landing flight regime. If required, the pilot or an automatic power compensation (throttle control) system can provide pseudo steady state control of angle-of-attack. Minimizing the induced angle-of-attack variations during maneuvering can be accomplished with a flight path (trajectory) control system consisting of blended direct lift and conventional control. It is possible to generate steady state normal acceleration and pitch rate for maneuvering along a descending flight path with minimum angle-of-attack variations using the concept presented in Figure 4. The required control is defined in terms of functional interconnects from the pilot controller to the pitch moment producing surface(s) and the direct lift surface(s). This type of blended control is also referred to as "command coupling".

If over-the-nose visibility and tail scrape angle are critical in approach rather than flight path stability, pitch attitude may be more desirable to control than angle-of-attack. To achieve constant pitch attitude requires a slightly different blending of steady state direct lift and conventional control as indicated in Figure 5. The command coupling interconnect shown is used to generate flight path control through normal acceleration and angle-of-attack changes without inducing significant pitch attitude changes. Thrust modulation by the pilot or an automatic flight control system may also be used to provide additional augmentation for maintaining a nearly constant pitch attitutde.

The previous examples show how direct lift control can be implemented in fighter-attack aircraft for carrier landing and how constraints on angle-of-attack and pitch attitude angle impact the blended control interconnect functions. The procedure demonstrated is conceptually applicable to other types of constraint relationships which can be used in the same manner to derive the blended control relationships.

DIRECT LIFT CONTROL IN TRANSPORT AIRCRAFT

Transport aircraft tend to be sluggish due to the high inertia and the long flight path time constant inherent in such vehicles. With conventional rotational control, a long flight path time constant increases the lag between aircraft pitch rate and subsequent normal load factor buildup. When commanding a pitching maneuver, the aircraft initially loses altitude and its dynamic response is noticeably sluggish in reaching steady state maneuvering conditions.

One operational system[2] uses direct lift control with conventional rotational control to generate faster normal acceleration response. This system provides precision flight path control and reduces the landing workload for the pilot. The system, functionally represented in Figure 6, utilizes spoilers and flaps which are both extended during landing. The spoilers are modulated symmetrically around a predetermined bias position to generate direct lift control. The value selected for washout time constant, used in blending the direct lift and conventional control, is such that the initial lift increase derived from direct lift control fades out when the lift increases from the angle of attack change generated by the tail surface becomes effective. The blending of the direct lift with the conventional control is mechanized to produce an overall improvement in aircraft pitch axis response by increasing the bandwidth without additional demand on the conventional control surface(s). With this type of mechanization, modulation of the spoilers produces about 0.1 g normal acceleration on the aircraft. Due to practical limitations (available lift, drag, and buffet), direct lift control is normally used to provide high frequency lift modulation while the tail surfaces are used for steady state control, pitch stabilization, and trim.

This particular direct lift control implementation utilizes redundant channel, fly-by-wire technology to provide the safety and reliability required for use during both manual and automatic landing. No separate cockpit controls and displays are required since this additional degree-of-freedom is blended into the basic flight control system and used during all landing modes.

DIRECT LIFT APPLICATION SUMMARY

Direct lift control in conventional aircraft has generally been used to improve flight path control during landing operations. The exact implementation is usually unique to the aircraft configuration and may incorporate any combination of the elements summarized in Figure 7.

The use of a single surface near the center of gravity, or multiple surfaces straddling the center of gravity, minimizes pitching moments while providing the lift required for a particular design. In such direct lift implementations, flight path control is generated with a control surface(s) which decouples the lift and pitching moment effects by geometric location.

In other mechanizations, this moment cancellation is performed with an existing conventional control surface using an interconnect from the flight control system. In this case, the direct lift surface (e.g. a canard) could be located forward of the center of gravity. An example of a generalized interconnect function, which could be programmed in a flight control computer for cancelling the moment effects generated by the direct lift surface(s) and for negating the lift effects from conventional moment producing surface(s) during a steady state maneuver is shown in Figure 8. The generalized aircraft motion parameter decoupling for the pitch axis is also presented. Decoupling the motion parameters involves continuous measurement of pitch rate and angle-of-attack with a sensor system and then using these signals as feedbacks in the flight control system for generating moment and lift control surface commands. The interconnect and cross feed equations shown reflect the aerodynamic lift and moment coefficients of the airframe. For pseudo constant flight conditions, such as landing approach, these coefficients produce nearly constant gain values. This technique can be applied throughout the flight envelope but system gain values will require scheduling as a function of flight condition.

In an open loop control system, the pilot controller commands are transmitted directly to the control surfaces. This technique gives the pilot both proportional and steady state control, and is being used in a number of first generation direct lift control systems. A washout is often used in series with the direct lift surface command to force the steady state deflection to zero. This produces transient direct lift response and blends it with the conventional control to improve handling quality characteristics. When a closed loop system is used, a feedback sensor such as a normal accelerometer, is incorporated. The controller then commands normal acceleration in lieu of surface deflection.

Direct lift commands can be generated manually using a spring loaded, return-to-center, wheel on the stick grip. (Figure 9). As described in Reference 3, this thumb operated wheel provides an electrical output which is proportional to the wheel rotation. Such an implementation is used in most of the open loop direct lift control designs. A number of the blended control approaches implement the direct lift commands from longitudinal stick deflections. In some cases, the direct lift commands are even automatic, being generated by a remote device on the ground and then transmitted to the aircraft over a data link.

LATERAL-DIRECTIONAL FLIGHT DYNAMICS

Analysis of the interaction of direct side force with lateral-directional flight dynamics requires the use of a mathematical model of the vehicle such as the one depicted in Figure 10. The small perturbation differential equations which describe the lateral-directional motion comprise the roll moment, yaw moment, and side force degrees-of-freedom.

The coordinate system identifies the rates, accelerations, and control surface deflections. Typically, the roll and yaw moment terms are inversely proportional to the inertia of the vehicle about these axes. As with the longitudinal terms, these also vary with dynamic pressure, surface area, and the non-dimensional aerodynamic derivative. The side force terms include the same proportional variation as the moment terms but vary inversely with aircraft mass and airspeed. These physical characteristics in turn determine the dynamic response characteristics to control surface and disturbance inputs.

The lateral-directional degrees-of-freedom are coupled through the airframe motion parameters and through the control surface deflection terms. Complete decoupling is achieved when one input generates one output without coupling into the remaining degrees-of-freedom. With the use of a direct side force surface in addition to the conventional surfaces, a complement of three surfaces is available for controlling three degrees-of-freedom. This is a requirement for implementing the new modes of control with innovative blending of the lateral-directional control surfaces as well as the lateral-directional degrees-of-freedom.

DIRECT SIDE FORCE APPLICATION SUMMARY

Direct side force applications have been analyzed, simulated, and flight tested on a number of vehicles. Although each implementation is somewhat different and is strongly influenced by the magnitude of direct side force that can efficiently be generated in the basic vehicle, there are common considerations (Figure 11) which impact the mechanizations of the various designs.

A number of implementations use a rudder or vertical tail surface for generating direct side force. In conjunction with this approach, additional wing surfaces or tip tank drag petals are required to cancel induced yawing moments but these provide only small levels of direct side force. A dedicated surface such as a vertical canard located near and ahead of the center of gravity is another viable technique used in some designs. Such a surface can be designed to provide effective levels of direct side force. The vertical canard surface can be interconnected to the rudder for mutual cancellation of yawing moments and complementary generation of direct side force.

The location of the surface on the vehicle must be compatible with the overall aerodynamic design and must not induce washout effects on other control surfaces. The size of the direct side force surface depends on the configuration and the lateral acceleration required. Medium to low aspect ratio surfaces seem to be favored since they provide adequate torsional stiffness and exhibit a lift curve slope which does not unduly compromise directional stability.

The direct side force surface must be properly integrated with roll moment and yawing moment surfaces. Efficient integration can require some degree of decoupling. The generalized decoupling expression presented in Figure 12 contains three equations which, when solved simultaneously, define the flight control system interconnect gains for decoupling the lateral-directional surface effectiveness terms. The interconnect relationships which result are the lateral-directional counterparts of the longitudinal relationships presented in Figure 8.

Blended direct side force, roll moment, and yaw moment control can be used to generate a more effective lateral flight path control capability. One type of application provides lateral translation control of the aircraft while minimizing heading and roll attitude deviations. In this mode, the pilot commands steady sideslip and wings level, constant heading, control of the aircraft. Implementation of steady sideslip control is accomplished using the command coupling technique shown in Figure 13. When these equations are solved simultaneously, the steady state interconnect expressions are derived for open loop control. These expressions, like the decoupling equations, are flight condition dependent; however, fixed values can generally be used over a limited range of airspeed and altitude variations. Lateral translation control was flight tested in the CALSPAN Total In-Flight Simulator (TIFS) aircraft[4] to assess such control effectiveness for improving pilot control during crosswind landings. It was concluded that this type of control was useful in crosswind landings and was particularly beneficial when the test aircraft had simulated poor flying qualities.

Another type of lateral flight path control, utilizes blended direct side force to generate wings level turning. This type of flight control system is designed to provide pilot control of yaw rate with minimum sideslip and roll attitude deviations. The command coupling equations used are presented in Figure 13. This concept was flight tested[5] in a simulated dive bombing mission using the CALSPAN T-33 Variable Stability Aircraft. It was concluded from this testing that the pilot is able to control lateral flight path more precisely. The improvement realized was largely based on the pilot having to make just one correction (wings level) for lateral target displacement rather than the conventional two bank angle maneuver while not impeding his tracking solution. In conventional aircraft, one banking maneuver is required to start translating in the desired direction and second banking maneuver in the opposite direction is required to stop it. The geometry of the problem is such that the banking of the aircraft adversely disturbs the dive bombing

solution. As a result, the pilot with conventional controls must use intense concentration to maintain the desired pointing direction of his vehicle.

Cockpit controllers which showed potential for operational use of direct side force included a thumbwheel located on the stick and operated in a left and right direction. In lateral translation control (steady sideslip), the thumb motion generated the direction of sideslip, while in a steady yaw rate control it commanded the direction of the yawing. The thumbwheel was spring-loaded to return to center and a detent indicated the null position. During crosswind landings, the direction of the thumbwheel rotation commanded the nose pointing direction of the aircraft. For example, thumbwheel deflection to the right commanded the aircraft to develop the sideslip in a direction to point the aircraft nose to the right. Rudder pedal control of direct side force was also investigated and found to have merit. Extra care had to be exercised to achieve the proper control sensitivities to permit rapid corrections while still maintaining fine control required for the dive bombing solution.

VECTORED LIFT FIGHTER CONFIGURATION CONCEPT

The Vectored Lift Fighter (VLF) concept evolved from McAir related studies to integrate high payoff, mature technologies into more effective fighter-attack configurations. In the VLF, the pilot has complete and independent control of all six aircraft degrees-of-freedom. As described in Reference 6, new control modes have been devised to exploit these additional degrees-of-freedom throughout the operational flight envelope. The concept has been validated by wind tunnel tests and manned simulation. The VLF is a highly integrated, but simple, Control Configured Vehicle (CCV) that is rendered practical by fly-by-wire and associated new technologies. The configuration requires only six control surfaces to provide all six independent degrees of flight control. In contrast, some of the most recent operational fighters require the coordination of nine to eleven surfaces to provide control of the conventional four degrees-of-freedom.

In VLF configuration shown in Figure 14, particular emphasis was placed on obtaining an aerodynamic configuration with high levels of direct lift and direct side force. Advanced aerodynamic features, such as the long chord inner wing combined with the moderately blended wing/body, permits controlled flight at high angles-of-attack. The single panel elevator located directly behind the long-chord wing, gives effective pitch control and recambering ability. The chin canard, in conjunction with the twin vertical tails, provides a high level of side force. Wind tunnel tests show that locating the engine nacelles at the wing mid-span provides low drag, end plates the inner wing, and establishes a wiping surface for the movable outer wing which negates aerodynamic losses normally associated with unported control surfaces. Normal shock inlets were selected for their low cost, low risk and tolerance of maneuvers at large pitch and yaw angles. The nacelle location also avoids the wake interference from the forward-located vertical canard.

The VLF is aerodynamically controlled in pitch with an all moveable elevator which generates rotational moments in response to: (1) basic pitch commands from the pilot (2) stability augmentation required at various flight conditions and g maneuvers, and (3) the control surface blending needed for operation in the various modes defined for the vehicle. The pitch axis is controlled throught elevator and symmetric variable incidence wing (VIW) deflections. The left and right side variable incidence (movable outer) wing commands are composed of both pitch (symmetric) and roll (differential) inputs. Yaw control is provided by three control surfaces (one vertical canard surface and two vertical tails). In yaw, as in pitch, the availability of multiple control surfaces makes possible the blended control mode technology incorporated into the VLF vehicle.

The VLF concept developed by McAir incorporates a low cost, light weight blend of conventional, advanced metallic, and advanced composite structural concepts. The control surfaces are full depth honeycomb construction with graphite epoxy face sheets and aluminum core. The primary feature of the VLF that achieves the added flight mode capability is the variable incidence wing. This wing design combines capability with simplicity. It is similar in size, rotational rate, hinge moment, and deflection to the horizontal stabilators on the F-15 and F-111 aircraft. The structural design criteria developed for the VLF ensures desired load factor and speed capability, design life, and structural integrity in all modes of operation.

Control system implementation using fly-by-wire technology makes control of the simple vectored lift configuration practical and effective. In the flight control system (Figure 15), the aerodynamic control surfaces are driven by hydraulic actuators which are sized to accommodate the required rates and deflections for multimode operation. Signal conversion mechanisms incorporating dual and triplex servos convert the electrical commands from the flight control computers into mechanical inputs to the actuators. The cockpit controls and displays are integrated with the flight control system computer to provide the pilot with an effective capability keyed to the multimode mission requirements of the VLF.

CONVENTIONAL CONTROL

Comparative evaluation of the multimode control capability with equivalent "conventional" control is one technique for determining the relative improvement attainable from the use of additional degrees-of-freedom.

In the pitch axis, the use of pitch rate and normal acceleration feedback in combination with elevator control generates a capability which is comparable to the control approaches used in conventional fighter aircraft. In such designs (Figure 16), pitch rate feedback provides primary short period stability augmentation. Normal acceleration feedback improves handling qualities by making the response characteristic of the aircraft nearly uniform throughout the aircraft's flight regime. Forward loop integration maintains zero steady state error between the force command and the blended pitch rate and normal acceleration feedback. Thus, the aircraft is automatically trimmed since any uncommanded combination of pitch rate and normal acceleration is automatically reduced to zero by the integration function. This configuration also provides neutral speed stability.

A typical root locus plot of the aircraft and flight control system at a subsonic and supersonic flight condition is shown in Figure 17. The frequency and damping of the closed loop roots which emanate from the basic aircraft short period poles represent the predominant oscillatory mode of the aircraft and flight control system combination. In the figure, the complex zero combination which attract the airframe poles are formed from the interaction of the pitch rate and normal acceleration feedback dynamics. The relaxed static stability incorporated in the VLF is reflected in the complex plane with one airframe pole being located on the positive real axis as shown for the subsonic flight condition. Without augmentation, an aperiodic divergence would cause the pitch axis to go unstable. To achieve a stable configuration, forward loop gain values of at least $K_F = 6.8$ or greater are required.

Conventional control provided by the lateral-directional implementation includes roll axis stabilization with roll rate feedback, dutch roll damping with high passed yaw rate feedback, and sideslip control with lateral acceleration feedback.

DUAL SURFACE CONTROL APPROACH

Without additional degrees-of-freedom, the "single" control surfaces available in pitch and yaw are relocated to conventional implementations as previously described. With the incorporation of direct lift and direct side force, dual surfaces are available for configuring new modes of control. The conventional relationship between trim angle-of-attack and elevator deflection for a specified incremental normal load factor is shown plotted as a line in Figure 18(a). When elevator and symmetric variable incidence wing deflections are varied, this line expands into the area relationship shown in Figure 18(b). As shown in Figure 18(b), constant normal load factor can be satisfied at various fuselage angle of attack values when dual surfaces are used. Conversely, constant angle-of-attack does not necessarily imply a predetermined constant normal load factor. The upper and lower limits of normal load factor bound the relationship in both cases and the overall size of the area for the dual surface deflections reflects the magnitude of the direct lift capability incorporated in the basic design.

Figure 19 shows the amount of direct side force resulting from the combined use of the vertical canard and vertical tail. Here, too, the conventional aircraft functional relationship of lateral load factor to sideslip angle is transformed from a line into an area with the use of dual surfaces. The size and shape of the area reflects the amount of direct side force inherent in the VLF vehicle.

Innovative flight modes can be formulated with this dual surface capability. Regardless of how new modes are conceived, they can be represented by transition paths emanating from the trim flight point inside the dual surface area and terminating at a new point corresponding to the steady state maneuvering conditions. Thus the conventional mode shown in Figure 20 can be identified as the transition path which falls on a line corresponding to conventional control (cc) surface deflections with direct lift and direct side force deflections of zero. The advanced VLF modes consisting of maneuver enhancement, normal/lateral translation, and fuselage aiming are shown to follow similar paths but do require dual surface control. Command coupling and decoupling techniques such as those previously described were utilized in the control law definition for these modes of operation. Open loop forward feed interconnects provided effective control of the aerodynamic surface interactions. Closed loop feedback of rotational rates and accelerations assisted in shaping the dynamic response of the aircraft motion parameters as well as providing stabilization throughout the flight envelope. A number of gain values in the flight control system were scheduled to achieve effective control over wide variations of flight conditions.

MANEUVER ENHANCEMENT CONTROL (MEC)

The maneuver enhancement control mode in pitch is implemented with blended direct lift and conventional control to achieve rapid normal load factor response with deadbeat damping of pitch rate. Rapid normal load factor response is required for flight path control during combat maneuvering. Well damped pitch rate is necessary for pitch attitude and precision tracking control. These capabilities constitute fundamental requirements which are applicable to most of the mission phases of the VLF and difficult to attain without the use of large magnitudes of direct lift. Maneuver enhancement control is mechanized to generate initial wing deflections for rapid normal acceleration onset followed by elevator deflection for harmonized pitch rotation and steady state control. The variable incidence wings are slowly returned to zero deflection while the elevator is deflected to maintain the required pitch rate. In effect, this combination of blended surface deflections produces and maintains the load factor response as commanded by the pilot with the side stick controller while simultaneously reducing the pitch rate overshoot as shown in Figure 21.

In the lateral-directional maneuver enhancement control design, direct side force and conventional moment control are blended to provide rapid roll rate response through lateral stick inputs and wings level yawing with minimum sideslip through rudder pedal deflections. Rapid roll rate response is desirable for roll attitude control and air-to-air precision tracking. Wings level yawing is needed for lateral flight path control during air combat and weapon delivery operations. The use of large magnitudes of direct side force facilitates the implementation of these lateral-directional capabilities and compliments the pitch axis design. The flight control system is mechanized to provide roll rate response with variable incidence wing deflections. Directional control is achieved with vertical tail deflections. The canard deflection is designed to neutralize the sideslip caused by the deflection of the vertical tails. In addition, a crossfeed from the canard to the vertical tails aids in cancelling the induced moments resulting from canard deflections.

NORMAL AND LATERAL TRANSLATION CONTROL

In this mode, the flight control system implementation enables the pilot with the use of an auxiliary thumb controller to command normal translation (direct lift) with minimal change in aircraft pitch attitude as shown in Figure 22. Thumb force commands applied to the two axes controller in the "up and down" direction generate normal translation. Commands in the "left and right" direction generate lateral translation. Normal translation control is integrated with the pitch axis MEC implementation. This integration permits the pilot to use either mode independently or to use both together. During normal translation mode operation, the pitch rate is minimized with MEC functions. The normal acceleration commanded with the thumb control is generated through angle-of-attack rate of change. Pitch axis control surface blending and pilot control harmonization for achieving this capability is provided by the flight control system design.

Two pilot control options are available in the normal translation control mode. In one option, manual deflection of the thumb controller commands normal velocity proportional to the magnitude of deflection. When no pilot control is applied, the normal velocity is reduced to zero. This option can be useful for performing such tasks as formation flying and refueling in which aircraft altitude positioning is critical. In the other option, manual deflection is functionally integrated to generate a command of normal acceleration. When no pilot control is applied, the normal acceleration is reduced to zero. If a vertical velocity was developed during previous use of the thumb controller, it would continue to cause climbing or diving flight until negated through additional pilot control. This option is used in tasks where the control of aircraft velocity is critical such as in weapon delivery.

In the lateral translation mode, the pilot commands sideslip, constant heading, and constant roll attitude. A thumb controller is used to generate sideslip modulation desired for lateral displacement maneuvering. The lateral translation control and the wings level yawing control of the MEC system are integrated to provide the constant heading and constant roll attitude capability. Similar to pitch axis control, the pilot can use lateral translation control or wings level yawing control independently, or both modes can be used together. The flight control system provides the overall blending of the control surfaces and pilot inputs to achieve an efficient implementation.

Two types of pilot control options are available in the lateral translation control mode. These options are similar to those available for normal translation control. In air-to-air mission phases where precise lateral displacement control is required, the proportional option is utilized. During air-to-ground operation where precise lateral velocity control is needed, the integral option is used.

FUSELAGE AIMING MODE (FAM)

The fuselage aiming mode implementation provides independent control of attitude and flight path angle in pitch and yaw, and features complete decoupling of the associated rotational and translational degrees-of-freedom.

The pilot role is an important consideration in the implementation of fuselage aiming mode. It was concluded during the VLF investigations that pilot control of flight path is a basic requirement for the integration of the additional degrees-of-freedom. As a result, this mode is configured to provide pilot control of normal acceleration with the side stick and lateral acceleration control with rudder pedals. This approach is compatible with normal flying techniques and provides consistency of control when transitional between the VLF modes.

With complete decoupling, rotational control can be dedicated toward optimizing the mission capability and operational role of the aircraft. Coupling the fire control system to attitude control in elevation and azimuth was selected for air combat operation. When engaged, the fire control system automatically commands attitude changes for precision tracking. The pilot provides flight path control as a coarse correction in concert with the overall tracking task. In air-to-air engagements this mode provides higher aspect conversion capability with more and longer duration firing opportunities than achievable with the same aircraft without the use of this mode. An example of the aircraft pitch axis response to independent command inputs from the pilot and the fire control system is shown in Figure 23.

Manual fuselage aiming in which the pilot uses the thumb controller to perform elevation and azimuth pointing was selected for air-to-ground operation. With this capability the nose of the aircraft can be depressed during strafing maneuvers. One of the problems associated with conventional weapons delivery techniques during shallow dive-angles is

that the bomb impact point disappears below the nose of the aircraft as the target is approached. The VLF, with manual fuselage aiming can lower the nose of the aircraft relative to the flight path to obtain more time for accurate weapon delivery operations.

AIR-TO-AIR AND AIR-TO-GROUND SIMULATION TESTING

The benefits of the Vectored Lift Fighter technologies in an air superiority environment were demonstrated during intensive one-on-one combat simulation against a high performance Advanced Day Fighter. The combat engagements were initiated at 20,000 ft (6096 m) altitude from various relative bearings. All engagements were aggressively fought in a guns only environment with each pilot trying to achieve and maintain a position of advantage. Regardless of target aspect, significantly more gun hits (within 20 ft of target center of gravity) were realized by the Vectored Lift Fighter with additional degrees-of-freedom than by the conventionally controlled Vectored Lift Fighter. The difference was particularly marked in a near head-on situation. The results obtained are summarized with respect to target aspect in Figure 24. The improved maneuverability and precise flight path control provided by the pitch MEC mode, and the increased accuracy of tracking with longer firing solutions offered by the fuselage aiming mode contributed to the improvement shown. Compared to the conventional version of the VLF aircraft in combat against the same opponent, the new technology VLF had a significant improvement in gun hits during air-to-air combat encounters.

The primary objectives of the air-to-ground simulation were to determine the benefits of the new control modes. The simulation data show significant improvement in steering performance and accuracy. The wings level steering feature of the Maneuver Enhancement Control mode obviates corrections required when the bank-to-turn procedure is used as in conventional aircraft. This feature contributes to the improved weapon delivery capability by significantly reducing the time required to steer out azimuth errors.

CONCLUSIONS

Additional degrees-of-freedom and fly-by-wire flight control system technology are being used in various aircraft designs to generate new maneuvering capabilities. Existing aircraft can benefit to a limited degree, but new aircraft designs such as the Vectored Lift Fighter, which incorporate these concepts initially in the configuration design, show the greatest potential benefits. The use of large magnitudes of direct lift and direct side force with innovative blending significantly improves air combat performance and weapon delivery. The VLF reflects a trend in future designs which provide new capabilities for pilot tactics and aircraft maneuvering performance to achieve greater agility and accuracy for accomplishing mission objectives.

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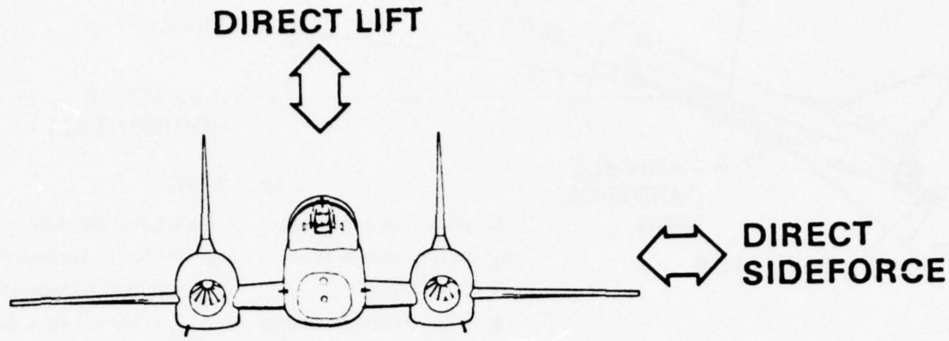


Fig.1 Additional degrees of freedom

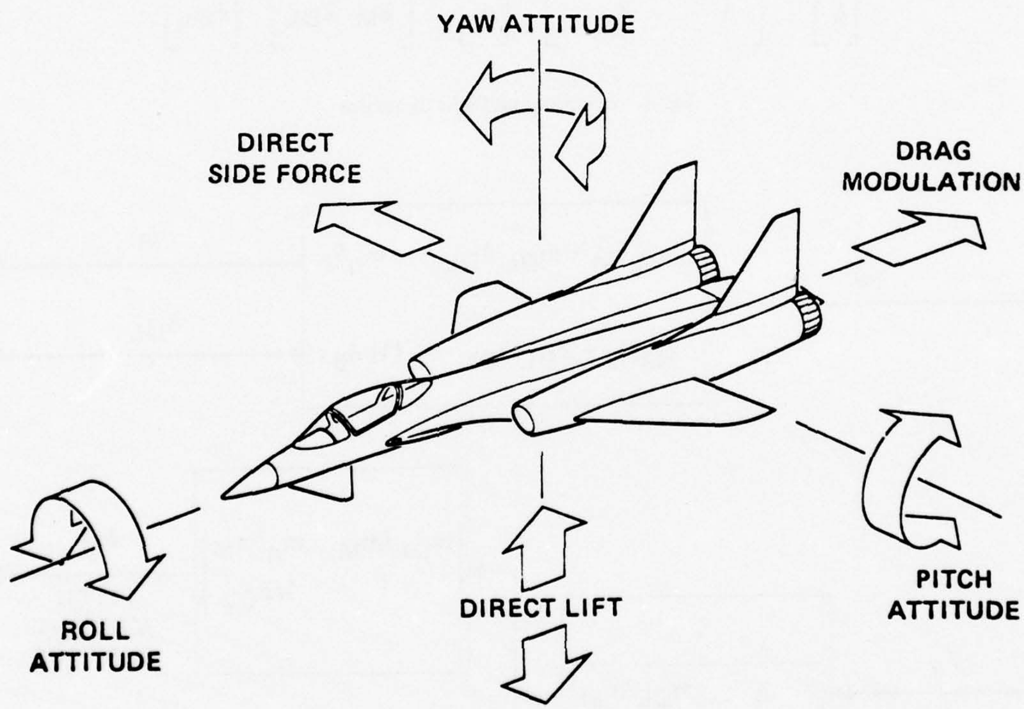
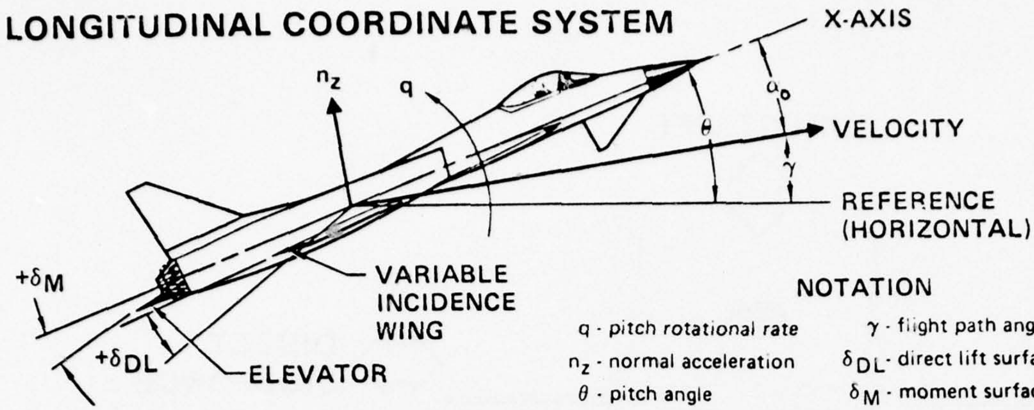


Fig.2 Vectored Lift Fighter (VLF) aircraft

LONGITUDINAL COORDINATE SYSTEM



NOTATION

q - pitch rotational rate	γ - flight path angle
n_z - normal acceleration	δ_{DL} - direct lift surface deflection
θ - pitch angle	δ_M - moment surface deflection
α - angle of attack change	$\Delta n_{z_{CG}} = V\dot{\gamma} = V(q - \dot{\alpha})$

EQUATIONS OF MOTION (SMALL PERTURBATION)

$$\begin{bmatrix}\dot q\\ \dot\alpha\end{bmatrix} = \begin{bmatrix} m_q & m_\alpha \lambda + m_\alpha \\ 1 & Z_\alpha\end{bmatrix}\begin{bmatrix}q\\ \alpha\end{bmatrix} + \begin{bmatrix} m_M & m_{DL}\\ Z_M & Z_{DL}\end{bmatrix}\begin{bmatrix}\delta_M\\ \delta_{DL}\end{bmatrix}$$

Fig.3 Longitudinal flight dynamics

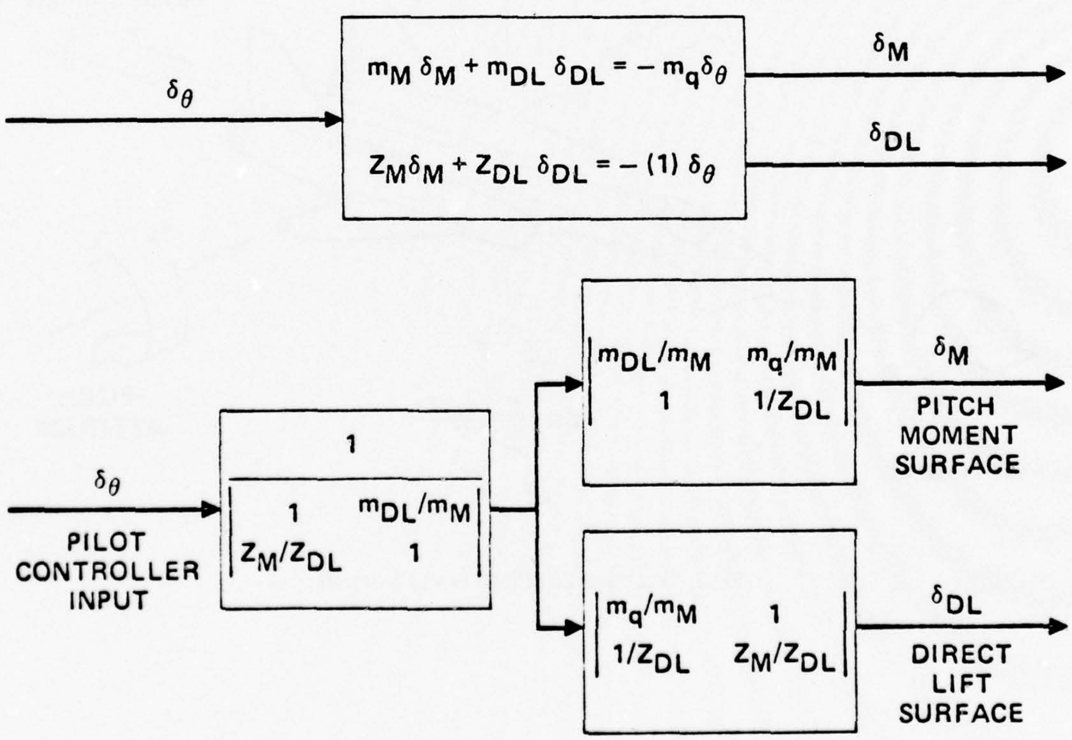


Fig.4 Controller to surface interconnect for flight path control during constant angle-of-attack operation

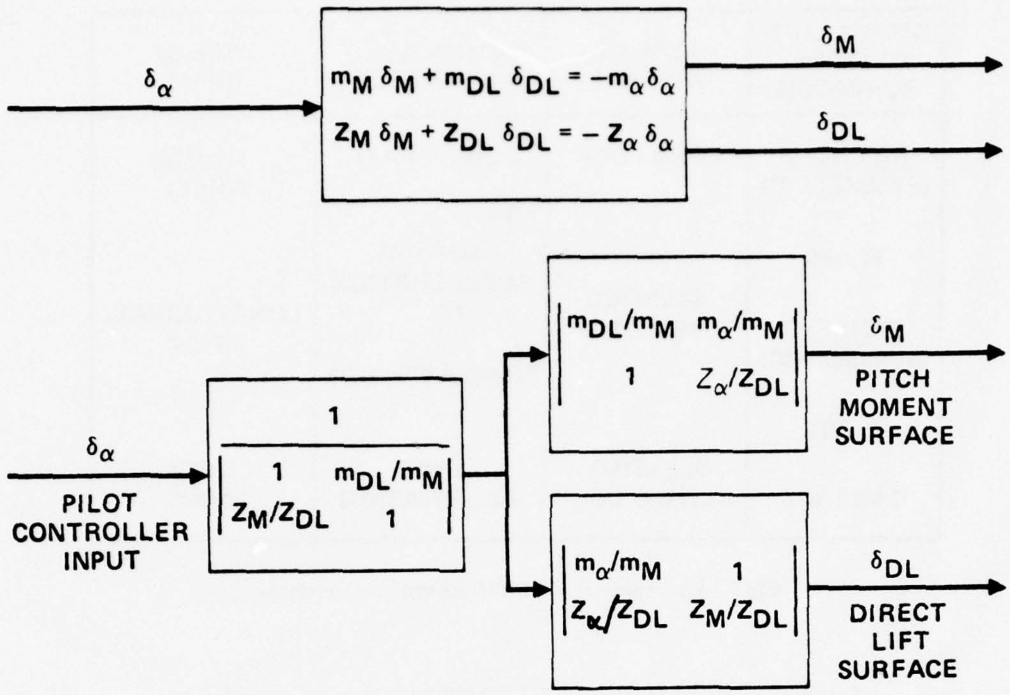


Fig.5 Controller to surfaces interconnect for flight path control during constant pitch attitude operation

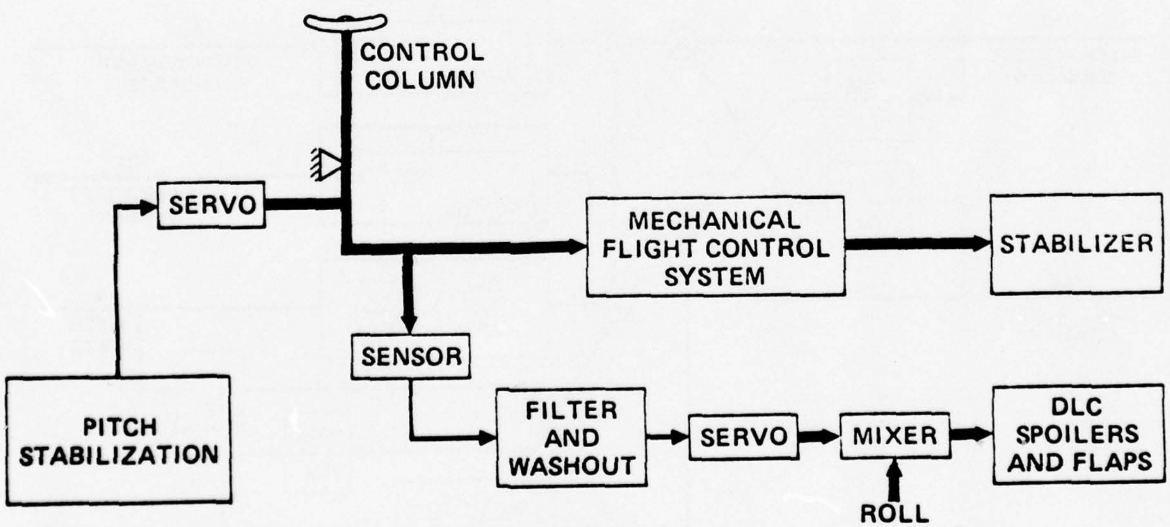


Fig.6 Transport aircraft direct lift system block diagram

DIRECT LIFT CONTROL SURFACE(S)	TYPE OF CONTROL	CONTROLLED PARAMETER	TYPE OF INPUT
AILERONS (SYMMETRIC)	OPEN LOOP	FLIGHT PATH	THUMB WHEEL
FLAPS		NORMAL ACCELERATION	
SPOILERS (SYMMETRIC)	BLENDED - OPEN LOOP	PITCH ATTITUDE	LONGITUDINAL STICK
SLATS			
CANARDS	BLENDED - CLOSED LOOP	GUST ALLEVIATION	DATA LINK

Fig.7 Conventional direct lift control considerations

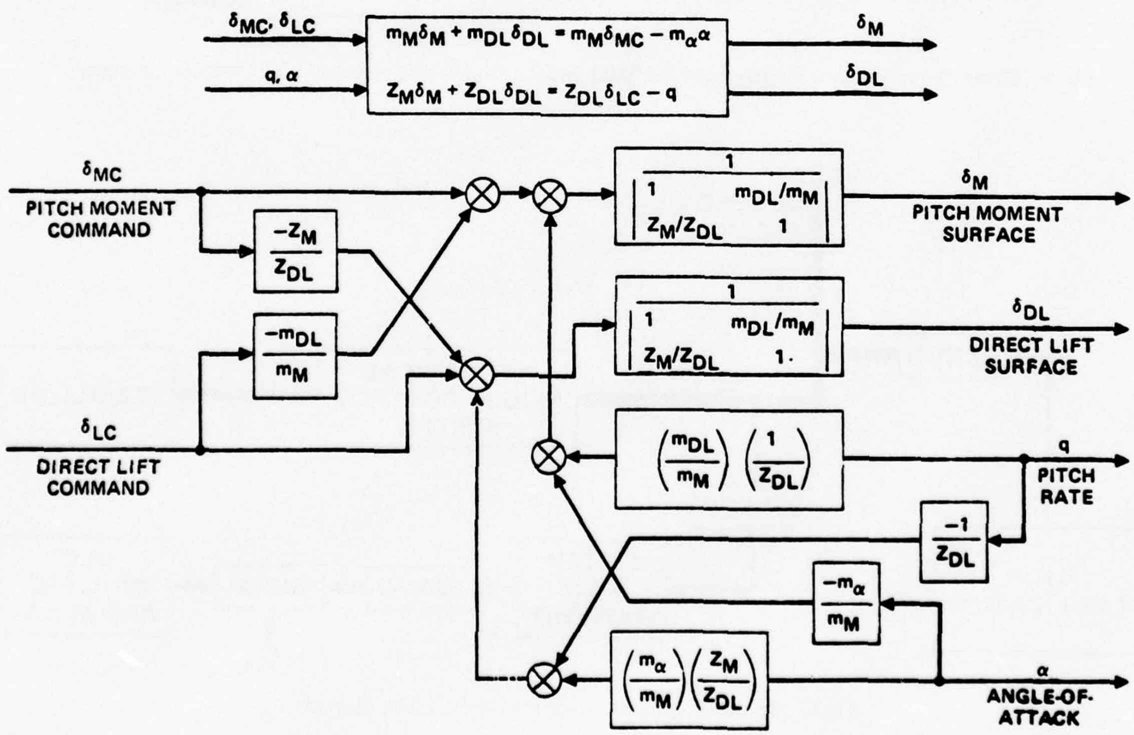


Fig.8 Interconnect techniques for decoupling pitch moment and lift degrees of freedom

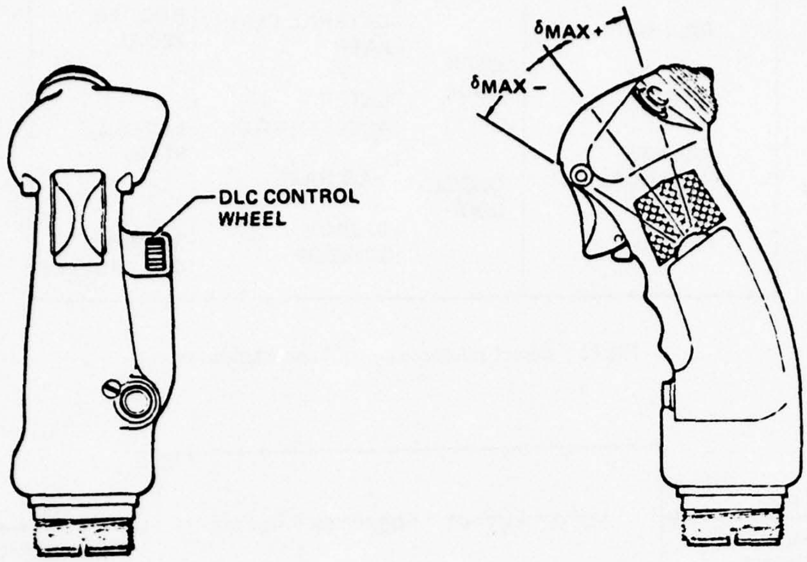
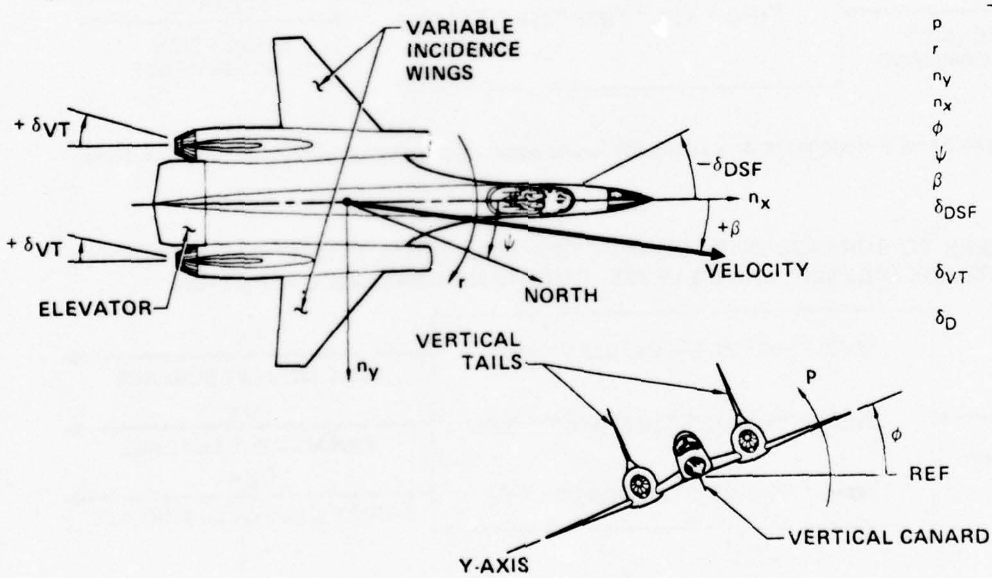


Fig.9 DLC wheel incorporated in fighter aircraft stick grip

LATERAL-DIRECTIONAL COORDINATE SYSTEM



NOTATION

- p - Roll rotational rate
- r - Yaw rotational rate
- n_y - Lateral acceleration
- n_x - Axial acceleration
- ϕ - Bank angle
- ψ - Heading angle
- β - Sideslip angle
- δ_{DSF} - Direct sideforce canard surface deflection
- δ_{VT} - Vertical tail deflection
- δ_D - Differential variable incidence wing deflection

EQUATIONS OF MOTION (SMALL PERTURBATION)

$$\begin{bmatrix} \dot{p} \\ \dot{r} \\ \dot{\beta} \end{bmatrix} = \begin{bmatrix} L_p & L_r & L_\beta \\ N_p & N_r & N_\beta \\ (\alpha_o + Y_p) + g/\lambda V & (Y_r - 1) & Y_\beta \end{bmatrix} \begin{bmatrix} p \\ r \\ \beta \end{bmatrix} + \begin{bmatrix} L_D & L_{VT} & L_{DSF} \\ N_D & N_{VT} & N_{DSF} \\ Y_D & Y_{VT} & Y_{DSF} \end{bmatrix} \begin{bmatrix} \delta_D \\ \delta_{VT} \\ \delta_{DSF} \end{bmatrix}$$

Fig.10 Lateral-directional flight dynamics

DIRECT SIDEFORCE CONTROL SURFACE(S)	TYPE OF CONTROL	CONTROLLED PARAMETER	TYPE OF INPUT
AILERONS	OPEN LOOP	LATERAL FLIGHT PATH	RUDDER PEDAL
RUDDER		LATERAL ACCELERATION	LATERAL STICK
CANARD (VERTICAL)	CLOSED LOOP	YAW RATE	
PETALS		STEADY SIDESLIP	THUMB CONTROLLER

Fig.11 Direct sideforce control considerations

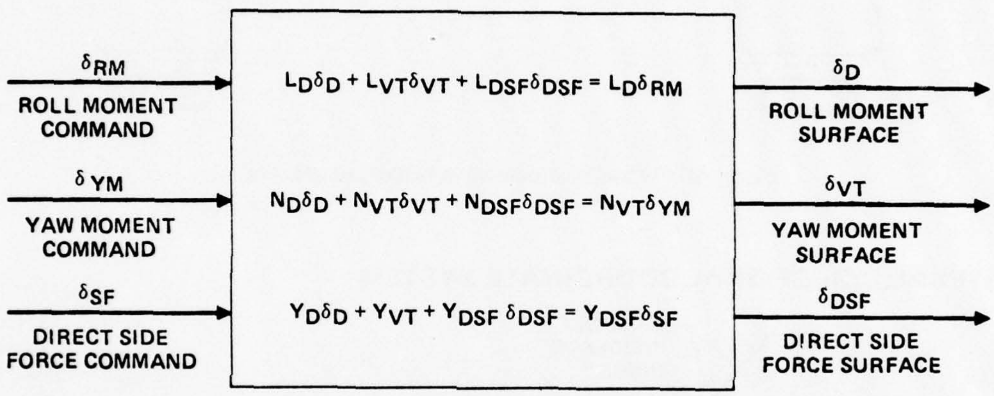


Fig.12 Interconnect technique for decoupling the lateral-directional aerodynamic control surface effects

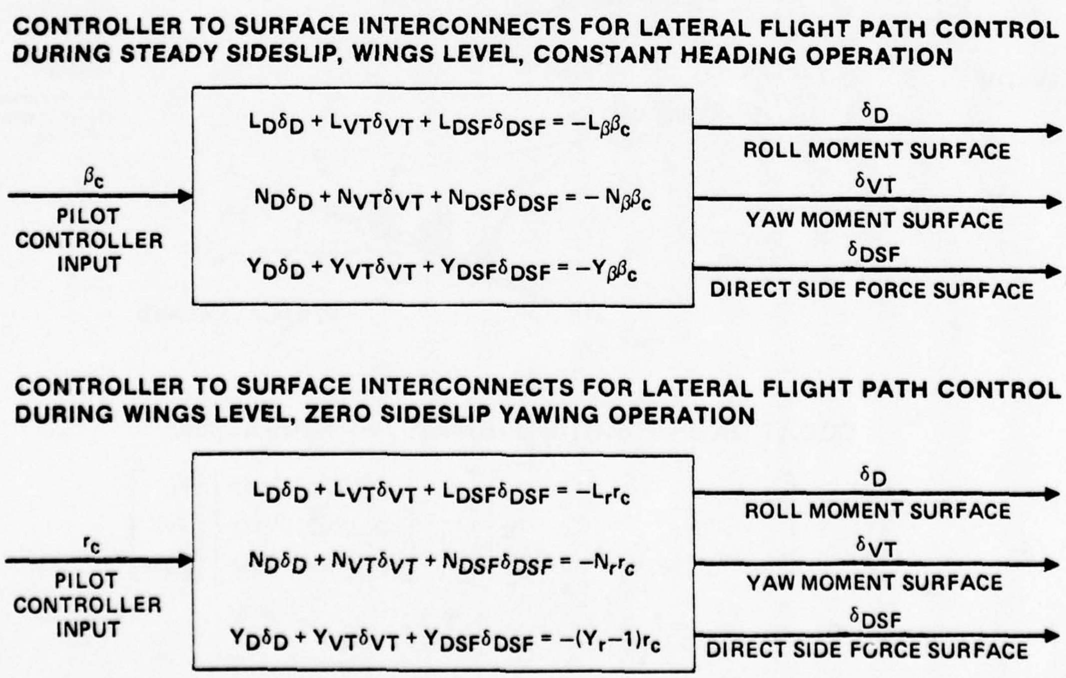


Fig.13 Direct side force control concepts

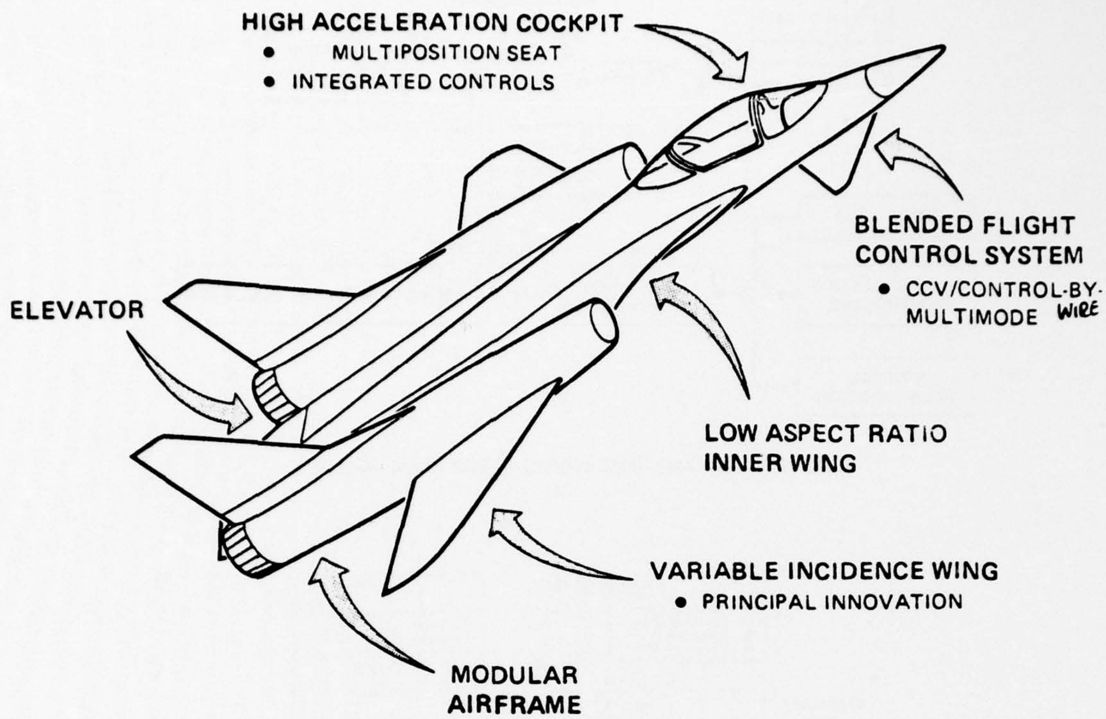


Fig.14 Vectored lift innovation in fighter design

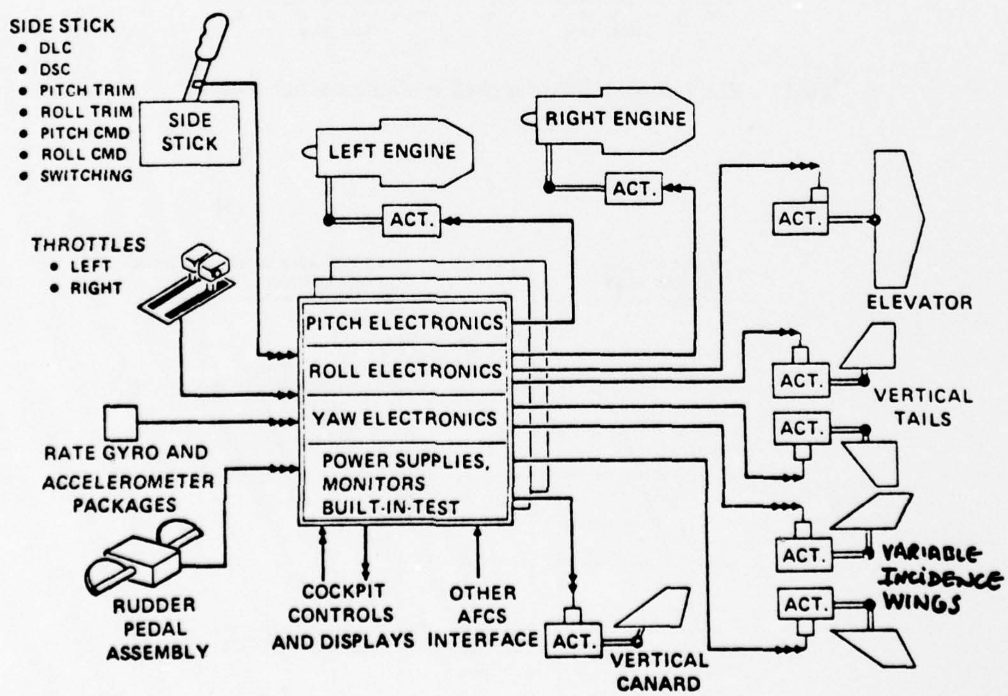


Fig.15 VLF flight control system mechanization

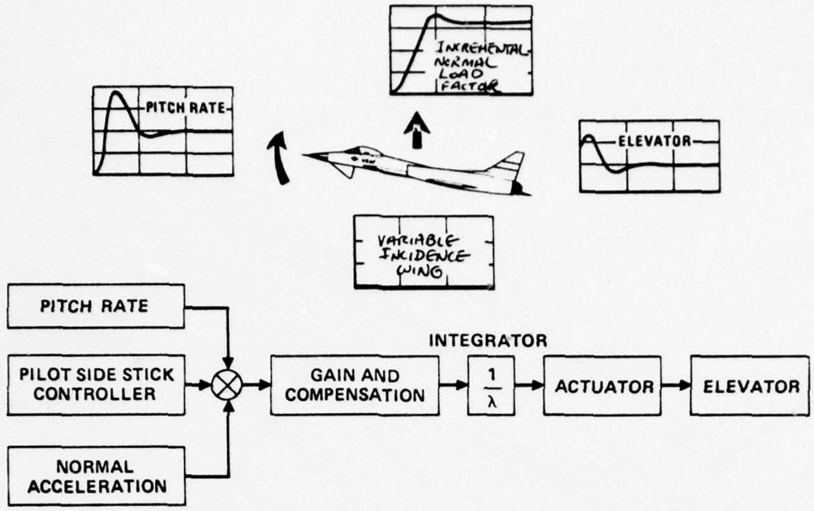


Fig.16 Pitch axis flight control system block diagram

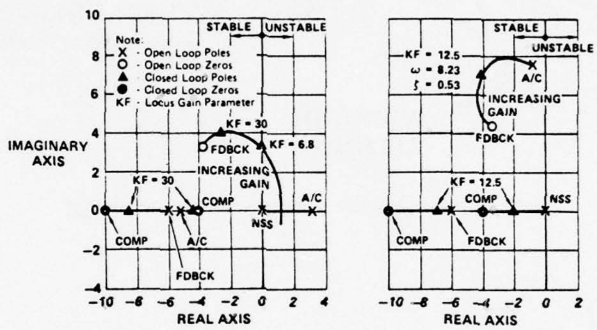


Fig.17 VLF root locus plots for pitch axis flight control system

(a)

(b)

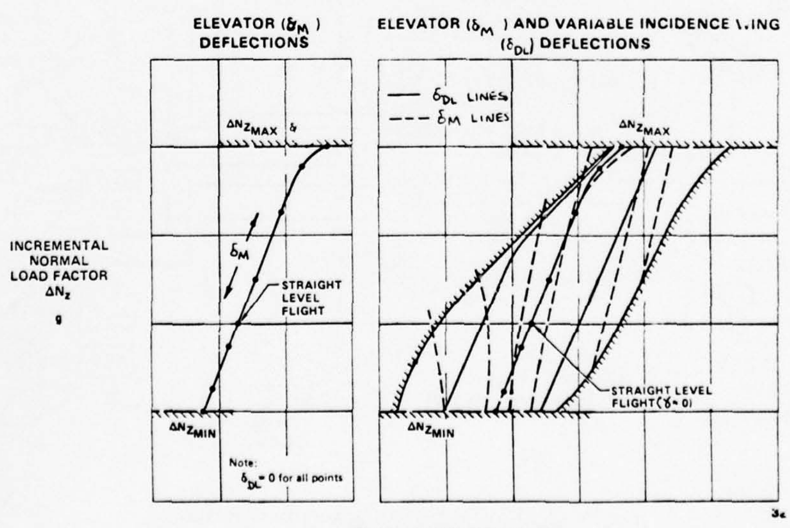


Fig.18 VLF trim angle-of-attack and incremental normal load factor specified surface deflections

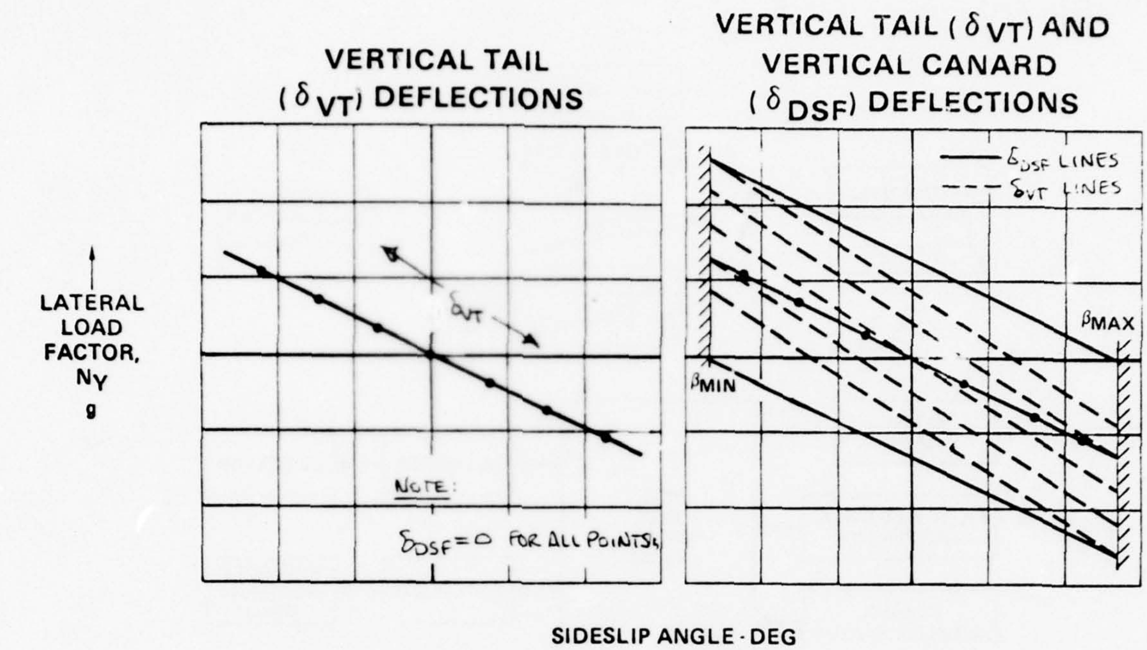


Fig.19 VLF trim sideslip angle and lateral load factor for specified surface deflections

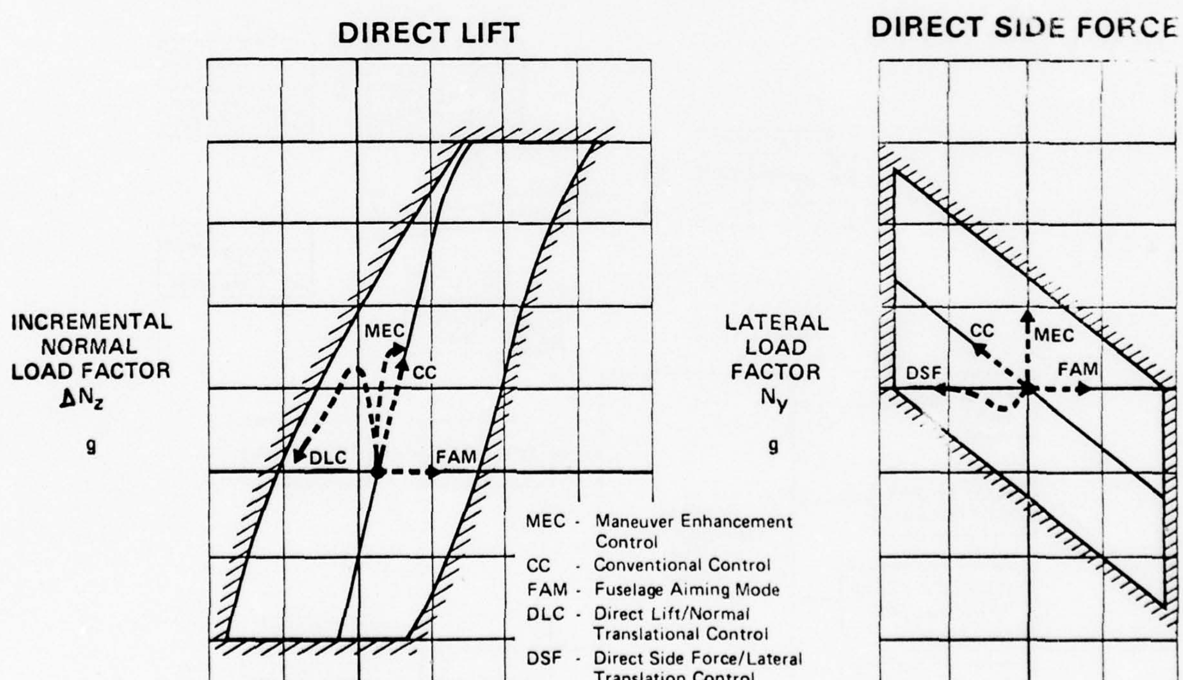


Fig.20 New modes of operation

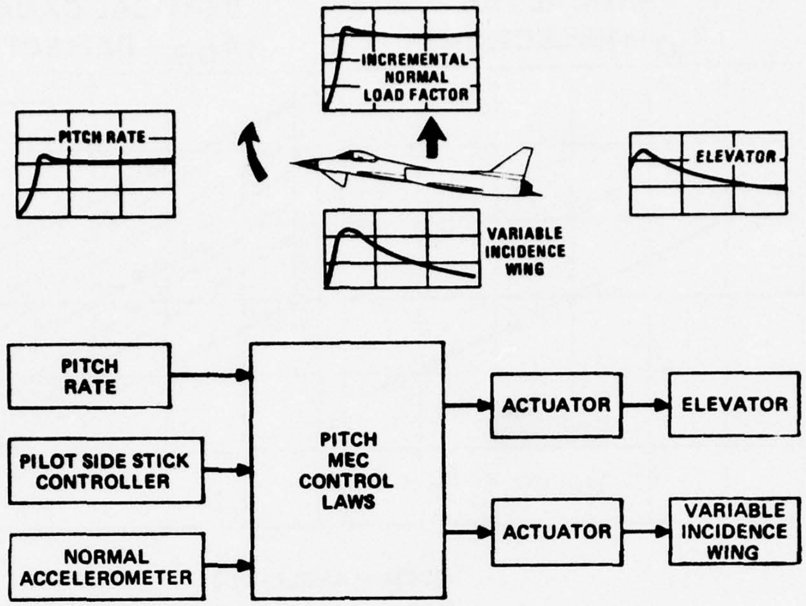


Fig.21 Maneuver enhancement control system

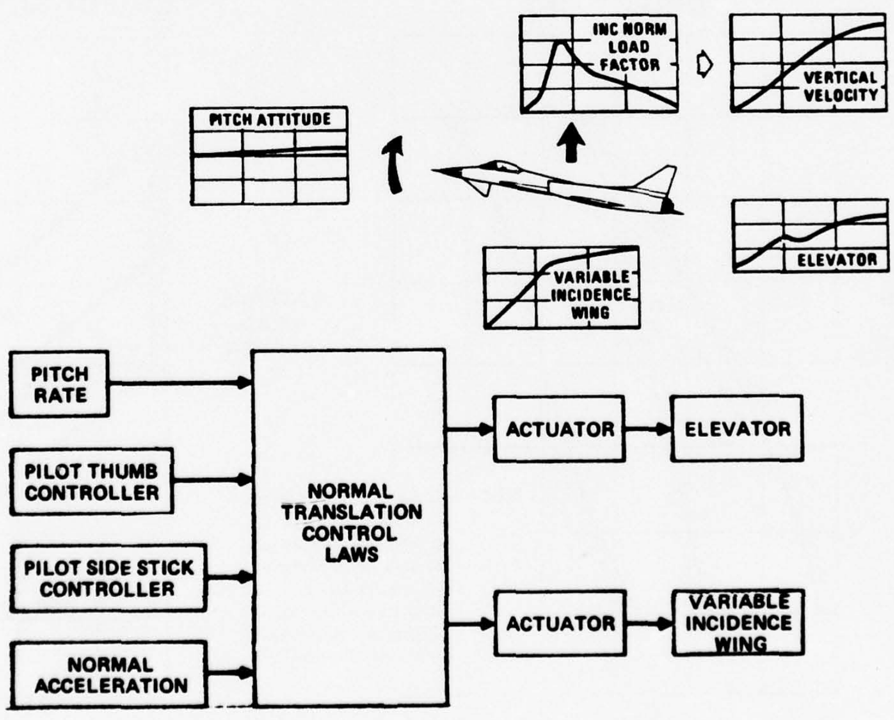


Fig.22 Direct lift (normal translation) control system

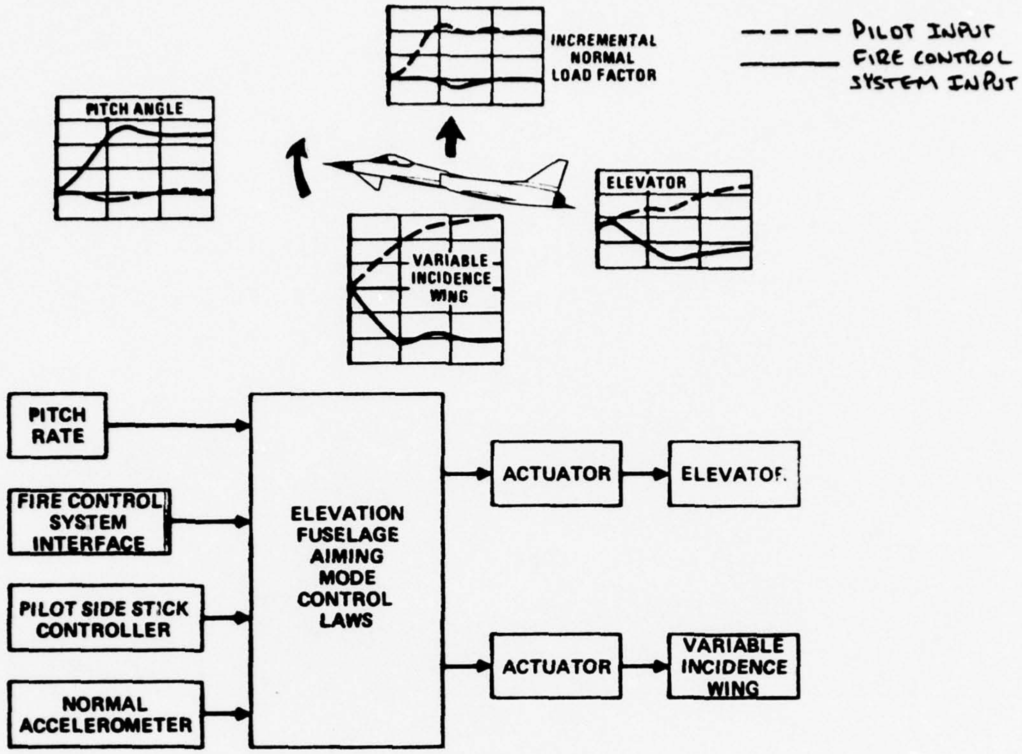


Fig.23 Elevation Fuselage Aiming Mode (FAM) control system

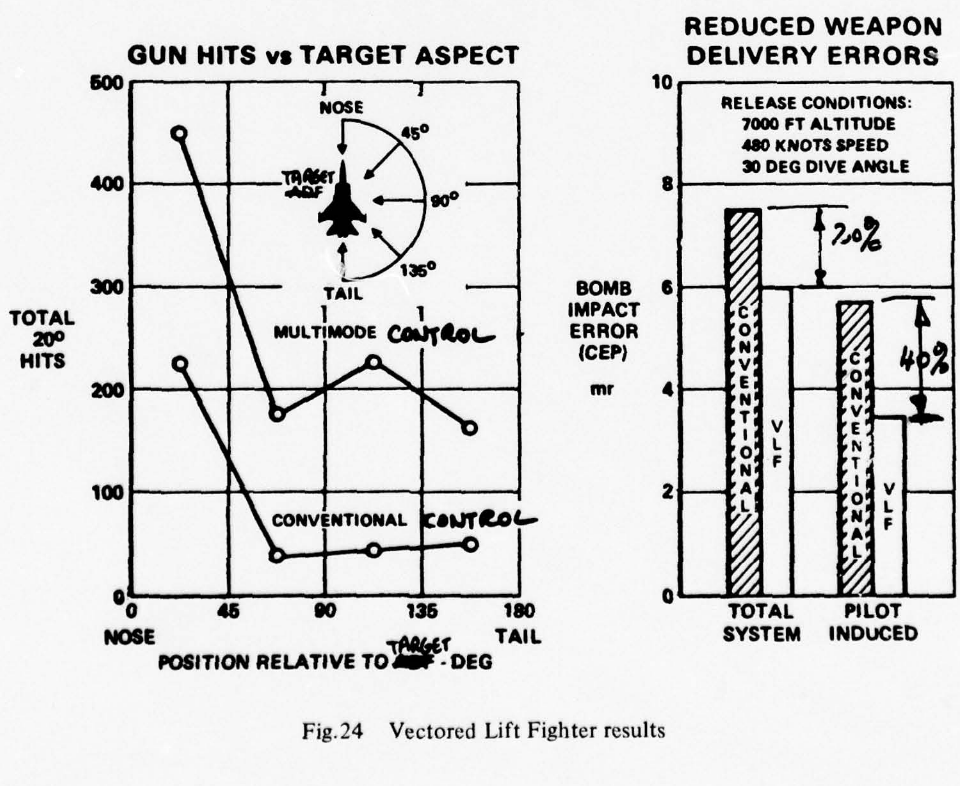


Fig.24 Vectored Lift Fighter results

BIBLIOGRAPHY ON TASK ORIENTED FLIGHT CONTROL SYSTEMS

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CONTENTS

1. INTRODUCTION

This bibliography has been compiled by the Defence Research Information Centre to provide literature references in support of the AGARD Lecture Series No. 89 on "Task Oriented Flight Control Systems". The aim of the lecture series is to discuss the benefits, problems, design and engineering aspects of recent developments in the flight control systems of manned aircraft. A broad review of the state-of-the art in modern flight control theory and practice will be given. The new concepts of task-oriented control systems, and some recent relevant simulator and flight trials will also be discussed.

2. SOURCES AND AVAILABILITY OF REFERENCES LISTED

The bibliography has been compiled using the European Space Agency RECON information network terminal at DRIC, and is based on the NASA-STAR/IAA file. The references are of items announced in the period January 1968 to December 1976.

(i) Items of the type N76-23057 were obtained from the bulletin Scientific and Technical Aerospace Reports (STAR), published by NASA.

(ii) Items of the type A76-14785 were obtained from the bulletin International Aerospace Abstracts (IAA), published by the American Institute for Aeronautics and Astronautics (AIAA).

Documents announced in STAR are drawn from the world's unpublished literature and are generally available from national libraries and information centres, usually in microfiche form. IAA covers the world's published literature, including periodicals and books, government sponsored journals, meeting papers and conference proceedings issued by professional societies and academic organizations, translations of journals and journal articles. The document source is quoted in each reference.

3. PRESENTATION

The citations, with abstracts are presented in reverse chronological order. An author index is included.

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INTEGRATED FLIGHT CONTROL SYSTEM DESIGN FOR CCV
Boudreau, J.A. (Grumman Aerospace Corp, Bethpage, N.Y.)
American Institute of Aeronautics & Astronautics,
Aircraft Systems and Technology Meeting, Dallas, Tex., Sep 27-29, 1976 15p

The advent of controlled configured vehicle (CCV) design approaches has imposed severe reliability and fault tolerance requirements on aircraft flight control and supporting systems. This paper establishes the requirements for, and develops the configuration of fine integrated fly-by-wire (FBW) flight control system suitable for an unstable CCV fighter/attack aircraft design. The hydraulic and electric power systems are an integral part of the design problem, since their functions are essential to safety of flight. A three-channel FBW system configuration was chosen as optimum. The system features in-line monitored active/on-line secondary actuators, skewed rate gyros and triplex digital computers, accelerometers and pilot input transducers.

2 A76-45378
THE CCV FIGHTER PROGRAM - DEMONSTRATING NEW CONTROL METHODS FOR TACTICAL AIRCRAFT
Swortzel, F.R Finley Carfield, A. (Flight Dynamics Lab. Wright-Patterson AFB, Ohio)
American Institute of Aeronautics & Astronautics, Aircraft Systems and Technology Meeting, Dallas, Tex., Sep 27-29, 1976, 10p

The fighter control configured vehicle (CCV) advanced development program is developing new control methods for tactical aircraft. Under contract to the Air Force Flight Dynamics Laboratory, General Dynamics is accomplishing the effort on a modified YF-16 aircraft. Control concepts being evaluated include direct lift, direct sideforce, maneuver enhancement and relaxed static stability. A total of six manual and one automatic direct force control modes are being evaluated. This paper describes the design approach, features, and system mechanization. Pertinent results of the various simulation efforts and their influence on the system design and flight testing are covered. The analyses and ground tests used to validate the mechanization are discussed. A summary of the flight test results to date and the possible applications of these new modes are presented.

3 A76-45376
FLIGHT TEST STATUS OF THE FIGHTER CCV
Thigfen, D.J., Whitmoyer, R.A.
American Institute of Aeronautics & Astronautics, Aircraft Systems and Technology Meeting, Dallas, Tex., Sep 27-29, 1976, 8p
USAF Supported Research. AA(General Dynamics Corp., Fort Worth, Tex.) AB(USAF, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio) 8p.

The control configured vehicle (CCV) advanced development program of the Air Force Flight Dynamics Laboratory is flight testing a modified YF-16 aircraft to investigate CCV concepts applied to fighter aircraft. General Dynamics Corporation has modified the YF-16 number 1 prototype with the addition of a CCV auxiliary flight control system to permit flight evaluations of three direct lift control (DLC) modes, three direct sideforce control (DSFC) modes, a maneuver enhancement/gust alleviation mode, and relaxed static stability conditions. Fin extensive flight test program began in March 1976 and will continue into 1977. This paper reports the progress of the CCV YF-16 flight test program and includes preliminary test results.

4 A76-45404
FLIGHT TEST DEVELOPMENT AND EVALUATION OF A MULTIMODE DIGITAL FLIGHT CONTROL SYSTEM IN AN A-7D
Damman, L.M.
American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Meeting, Dallas, Tex., Sep 27-29, 1976, 12p.
AA(USAF, Flight Test Center, Edwards AFB, Calif.) 12p.

A flight test development and evaluation of a multimode digital flight control system (DFCS) installed in an A-7D was conducted by the Air Force Flight Test Centre. This system used dual minicomputers to duplicate standard A-7D analog flight control system modes as well as provide two additional advanced control modes. This paper will summarize the ground and flight test techniques used and some specific results. In addition, features which proved beneficial for this type of development program will be highlighted. The results will be extracted from the 92 hour flight test program which was the first Air Force test and evaluation of a digital flight control system in a tactical fighter aircraft.

5 A76-41485
ANALYSIS OF OPTIMAL EVASIVE MANEUVERS BASED ON A LINEARIZED TWO-DIMENSIONAL KINEMATIC MODEL
Shinar, J., Steinberg, D. (Technion - Israel Institute of Technology, Haifa, Israel)
In: Guidance and Control Conference, San Diego, Calif., August 16-18, 1976 Proceedings. (A76-41426) New York, American Institute of Aeronautics and Astronautics, Inc., 1976, 546-554p 15 refs. (AIAA 76-1979)

Optimal evasion from homing missiles is analysed assuming 2-D linearized kinematics. Instead of solving two-point boundary value problems, simple search technique is used. The simplicity of this approach enables factors frequently neglected in analytical studies to be considered including exact system dynamics structure, location of saturation elements, limited evader roll-rate, etc. Validity of analysis is limited, but not more than of nonlinear 2-D models, to nearly 'head-on' or 'tail chase' situations. Engagements with other initial conditions require 3-D modeling. The method presented in this paper can be extended for such 3-D analysis.

6 A76-41441
SOFTWARE CONTROL PROCEDURES FOR THE JA-37 DIGITAL AUTOMATIC FLIGHT CONTROL SYSTEM.
Bailey, D.G. (Honeywell, Inc., Minneapolis, Minn.) and Folkesson, K. (Saab-Scania AB, Goteborg, Sweden).
In: Guidance and Control Conference, San Diego, Calif., August 16-18, 1976, Proceedings. (A76-41426) New York, American Institute of Aeronautics and Astronautics, Inc., 1976, 122-129p (AIAA 76-1930)

The software control procedures described were developed for the high authority fail-safe single-processor digital control system of the JA-37 Viggen interceptor. The control system authority is close to 10g at low altitude high-speed flight conditions. The procedures involve software organization, documentation, and change procedures. A functional computation flow chart of the control system is discussed.

7 A76-41461
DEVELOPMENT AND EVALUATION OF PRECISION CONTROL MODES FOR FIGHTER AIRCRAFT
Merkel, P.A., Whitmoyer, R.A. (USAF, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio).
In: Guidance and Control Conference, San Diego, Calif., August 16-18, 1976, Proceedings. (A76-41426 20-12) New York, American Institute of Aeronautics and Astronautics, Inc., 1976, 300-308p (AIAA 76-1950)

The Control Configured Vehicle (CCV) Advanced Development Program of the Air Force Flight Dynamics Laboratory is developing advanced flight control concepts for fighter aircraft. A current contracted effort with General Dynamics Corporation has modified a YF-16 aircraft to flight evaluate six uncoupled maneuver modes and an automatic control mode for precision flight path control. This paper describes the design and development of the CCV YF-16 auxiliary Fly-by-Wire flight control system including simulation studies and redundancy tradeoffs. Also discussed are the operational applications of the maneuver modes and preliminary flight test results.

8 A76-36901
ATMOSPHERIC FLIGHT MECHANICS CONFERENCE 3RD, ARLINGTON, TEX., JUNE 7-9, 1976 PROCEEDINGS
Conference sponsored by the American Institute of Aeronautics and Astronautics. New York, American Institute of Aeronautics and Astronautics, Inc., 1976 236p

Papers are presented on jump phenomena in roll-coupled maneuvers of aircraft, nonoptimality of steady-state cruise for aircraft, estimation of the stochastic control of an aircraft flying in atmospheric turbulence, and the stall/spin characteristics of fighter aircraft. Also examined are an aerodynamic parameter identification for the A-7 aircraft at high angles of attack, determination of tail-off aircraft parameters using systems identification, and the effects of aircraft design and atmospheric turbulence on handling and ride qualities. Ablation-induced roll torques on reentry vehicles, Space Shuttle Orbiter entry guidance and control system sensitivity, and an automated scheme to determine design for a recoverable reentry vehicle are also considered. Individual items are announced in this issue.

9 N76-29245
STALL/SPIN PROBLEMS OF MILITARY AIRCRAFT
Advisory Group for Aerospace Research and Development, Paris (France)
Jun. 1976 242p refs Presented at the Flight Mech. Panel Specialists Meeting. Rhode Saint Genese, Belgium, 18-21 Nov. 1975
(AGARD-CP-199) Copyright.

Stall/spin aspects of aircraft design are discussed in relation to the high angle of attack problem.

10 N76-29246
THE STALL/SPIN PROBLEM
Air Force Flight Dynamics Lab., Wright Patterson AFB, Ohio
Woodcock, R.J., Weissman, R. (ASD)
In AGARD Stall/Spin Probl. of Mil. Aircraft Jun. 1976 12p refs

Stall/spin problems still plague aircraft designers. The development of spin tunnel and free flight model testing techniques is traced, prospects of improved aerodynamics are indicated, and some flight control system capabilities outlined, with reference to experience with some recent airplanes. Recovery from spins and post-stall gyrations is emphasized but a need for more emphasis on designing for resistance to loss of control is advocated.

11 N76-29247
THE STALL/SPIN PROBLEM. AMERICAN INDUSTRY'S APPROACH
General Dynamics/Fort Worth, Tex.
Anderson, C.A.
In AGARD Stall/Spin Probl. of Mil. Aircraft Jun, 1976 8p

An attempt is made to detail what has caused stall/spin problems, what options are open to the aircraft designer to reduce stall/spin susceptibility, and some of the current evaluation criteria that are available. Also, the various analytical and experimental tools and flight test techniques available today are reviewed. An assessment is then made of the usefulness of each of these guidelines, tools, and techniques. Finally, a recommended procedure for determining the stall/spin susceptility and characteristics is presented.

12 N76-29248
COMPARISON OF THE SPIN AND LOW INCIDENCE AUTOROTATION OF THE JAGUAR STRIKE AIRCRAFT
Aeroplance and Armament Experiment Establishment, Boscombe Down
Blamey, R.J.
In AGARD Stall/Spin Probl. of Mil. Aircraft Jun. 1976 10p refs

From the extensive flight trials on Jaguar high incidence and spin behavior, a number of interesting results emerged. Compared is the classical high incidence spin mode with a rather less common low incidence autorotation which appeared during Jaguar evaluation trials.

13 N76-29249
A COMPARISON OF MODEL AND FULL SCALE SPINNING CHARACTERISTICS ON THE LIGHTNING
British Aircraft Corp., Preston
Burns, B.R.
In AGARD Stall/Spin Probl. of Mil. Aircraft Jun 1976 12p

Lightning spinning history is reviewed and a comparison is made of the characteristics as shown by vertical wind tunnel, helicopter drop model and full scale flight trials. The comparison is made in terms of both qualitative interpretation of the spin and recovery behaviour and measured data. It is shown that the three types of tests exhibited good qualitative agreement in all important respects. Only a limited quantitative comparison is possible because of limitations of the measured data and differences between the test techniques. The test results are related to service experience and some observations are made about the interpretation of spinning test results and the need for simplicity in pilot's operating notes.

14 N76-29250
DESIGN TECHNOLOGY FOR DEPARTURE RESISTANCE OF FIGHTER AIRCRAFT Aircraft Div.
Northrop Corp., Hawthorne, Calif.
Titriga, A., Ackerman, J.S. and Skow, A.M.
In AGARD Stall/Spin Probl. of Mil. Aircraft Jun 1976 13p refs

Methods are presented for predicting departure characteristics of aircraft during the design stages prior to model or flight tests. The significance of longitudinal pitching moment characteristics with respect to sideslip is discussed and correlated with flight test data. The use of departure parameters is discussed and examples are presented which show good correlation with flight test results. A computer graphics display of the aircraft driven by actual flight test data has proven to be extremely helpful in visualizing complex motions of an aircraft In particular this technique showing great promise in aiding both pilots and engineers in describing distorting post stall girations that may be encountered during stall/spin flight testing of an aircraft.

15 N76-29251
RESULTS OF RECENT NASA STUDIES ON SPIN RESISTANCE
National Aeronautics and Space Administration.
Langley Research Center, Langley Station, Va.
Chambers, J.R., Gilbert, W.P and Grafton, S.B.
In AGARD Stall/Spin Probl. of Mil. Aircraft Jun 1976 12p refs

Some of the factors which contribute to good stall/spin characteristics of a current fighter configuration indicate that the design of airframe components for inherent spin resistance is very configuration dependent and that few generalizations can be made. Secondary design features, such as fuselage forebody shape, can have significant effects of stability characteristics at high angles of attack. Recent piloted simulator studies and airplane flight tests have indicated that current automatic control systems can be tailored so as to provide a high degree of spin resistance for some configurations without restrictions to maneuverability. Such systems result in greatly increased pilot confidence and increased tactical effectiveness.

16 N76-29253
STALL BEHAVIOR AND SPIN ESTIMATION METHOD BY USE OF ROTATING BALANCE MEASUREMENTS
Aeronautica Macchi S. p. A., Varese (Italy)
Bazzocchi, E.
In AGARD Stall/Spin Probl. of Mil. Aircraft Jun. 1976 16p

Experimental work is reported in the field of wind tunnel investigation of stall behavior, in the evaluation of the characteristics of lateral control devices, in the measurement of the aerodynamic coefficients to determine lateral-directional stability and the analytical study of the spin. This research has required the development of special test equipment, measurement methods and calibration systems. A description and data is given on the test equipment adopted, its use and some of the results obtained.

17 N76-29256
LIMITING FLIGHT CONTROL SYSTEMS
Air Force Flight Dynamics Lab., Wright Patterson AFB, Ohio
Bowser, D.K.
In AGARD Stall/Spin Probl. of Mil. Aircraft Jun. 1976 12p refs

The development and application of various types of automatic flight control systems for high angle of attack augmentation and limiting are reported. Considerations included are improved handling qualities for maximum tracking effectiveness, reduced pilot workload, control configured vehicles, stall inhibitors, and departure prevention systems.

18 A76-33945
THE DESIGN AND DEVELOPMENT OF A MILITARY COMBAT AIRCRAFT. III - LONGITUDINAL STABILITY AND CONTROL
Burns, B.R.A. (British Aircraft Corp. Ltd., Military Aircraft Div., Preston, Lancs., England)
Interavia, vol. 31, June 1976 553-556p

Major considerations in designing a military combat aircraft for optimum handling qualities in terms of longitudinal stability and control are discussed. The reasons and palliatives for the common stability minimum at high subsonic speeds in low-altitude flight are considered. The relationship between stick forces and maneuver margin is described. The sizing and placement of the tailplane is examined in detail. Control approaches, including artificial stability, maneuver boost, maneuver demand, and autostabilization, are discussed

19 A76-32650
THE DESIGN AND DEVELOPMENT OF A MILITARY COMBAT AIRCRAFT. II. - SIZING THE AIRCRAFT.
Burns, B.R.A. (British Aircraft Corp., Ltd., Preston, Lancs., England)
Interavia, vol. 31, May 1976, 448-450p

The sizing of a military combat aircraft to meet mission requirements and minimize takeoff weight is discussed. The effects of design requirements and configuration features on the airframe, powerplant, and fuel weight fractions are considered. Attention is given to the tradeoff between fuel economy and the thrust/weight ratio in engine design and the advantages and disadvantages of external fuel carriage. The importance of achieving aerodynamic and structural efficiency and preventing weight and drag growth as the design progresses is stressed.

20 A76-24063
THE DESIGN AND DEVELOPMENT OF A MILITARY COMBAT AIRCRAFT. I. DESIGN FOR PERFORMANCE
Burns, B.R. (British Aircraft Corp., Ltd., Military Aircraft Div., Warton, Lancs., England)
Interavia, vol. 31, Mar. 1976, 241-246p

The design of military combat aircraft to meet the requirements of a specified point performance and mission performance is discussed. Special emphasis is given to the impact on the wing design of the maximum Mach number, specific excess power, and sustained and instantaneous maneuver. Methods of resolving wing design conflicts in aircraft intended for both subsonic and supersonic use are discussed. The advantages and disadvantages of under-fuselage and under-wing external store carriage positions are outlined.

21 A76-30704
ADVANCED FIGHTER PROGRAM STRESS SHIFTS
Wetmore, W.C.
Aviation Week and Space Technology, vol. 104, May 3, 1976, p88, 91, 95(3 ff.)

Combat versatility of the vectored lift fighter (VLF) is discussed, with diagrams. A shift toward use of existing aircraft as test beds (backed up by wind tunnel studies, analytical and flight simulation studies) is noted. The variable-incidence wing of the VLF cannot be tailored to existing aircraft. The six control surfaces (twin vertical stabilizers, beavertail elevator, outboard variable-incidence wing sections, vertical chin fin) offer six degrees of freedom in flight. This, plus advantages accruing from digital fly-by-wire controls plus an analog reversion mode, and relaxed longitudinal static stability margins, enhance VLF performance with such options as fuselage aiming, direct lift, direct side force (particularly useful for roll-free landing in crosswinds), thrust modulation and drag modulation in velocity control. Drag modulation via symmetric movements of the variable-incidence wings can cause an opponent aircraft attacking the VLF tail to overshoot, losing the combat advantage to the VLF. VLF combat advantages, confirmed in flight combat simulation tests, are listed separately.

22 N76-24266
SIMULATOR STUDY OF THE EFFECTIVENESS OF AN AUTOMATIC CONTROL SYSTEM DESIGNED TO IMPROVE THE HIGH-ANGLE-OF-ATTACK CHARACTERISTICS OF A FIGHTER AIRPLANE
National Aeronautics and Space Administration. Langley Research Center, Langley Station, Va.
Gilbert, W.P., Nguyen, L.T. and VanGunst, R.W.
Washington, May 1976, 156p ref (NASA-TN-D-8176: L-10545)

A piloted, fixed-base simulation was conducted to study the effectiveness of some automatic control system features designed to improve the stability and control characteristics of fighter airplanes at high angles of attack. These features include an angle-of-attack limiter, a normal-acceleration limiter, an aileron-rudder interconnect, and a stability-axis yaw damper. The study was based on a current lightweight fighter prototype. The aerodynamic data used in the simulation were measured on a 0.15-scale model at low Reynolds number and low subsonic Mach number. The simulation was conducted on the Langley differential maneuvering simulator and the evaluation involved representative combat maneuvering. Results of the investigation show the fully augmented airplane to be quite stable and maneuverable throughout the operational angle-of-attack range. The angle-of-attack/normal-acceleration limiting feature of the pitch control system is found to be a necessity to avoid angle-of-attack excursions at high angles of attack. The aileron-rudder interconnect system is shown to be very effective in making the airplane departure resistant while the stability-axis yaw damper provided improved high-angle-of-attack roll performance with a minimum of sideslip excursions.

23 N76-25266
FLIGHT/GROUND TESTING FACILITIES CORRELATION
Advisory Group for Aerospace Research and Development, Paris (France)
Apr. 1976 417p refs Presented at 46th Meeting of the Flight Mech. Panel, Valloire, France, 9-13 Jun. 1975
(AGARD-CP-187: ISBN-92-835-0163-2)

The Symposium was organized around three subject areas: (1) correlation of basic wind tunnel techniques, (2) flight test techniques for correlation and (3) wind tunnel/flight correlation. Papers were presented which treated specific studies designed to compare various two and three dimensional wind tunnel facilities, wind tunnel facilities designed to provide better Reynolds number matches with full scale, and techniques used to contain wall effects, measure dynamic characteristics and study noise. The state of the art with regard to parameter identification was summarized and the proceedings of the AGARD Flight Mechanics Panel Specialists' Meeting were reviewed. Also treated were methods of measuring aerodynamic characteristics, in flight, of wings, rotors, and special aircraft configured for the acquisition of data not normally available from flight tests. Correlation experience for a broad spectrum of aircraft types was reported. It was suggested that good correlation can be obtained if enough attention is given to ground tests.

24 N76-25298
EFFECTS OF BUFFETING AND OTHER TRANSONIC PHENOMENA
Air Force Flight Dynamics Lab. Wright Patterson AFB, Ohio.
Lamar, W.E. in AGARD Flight/Ground Testing Fac. Correlation Apr. 1976, 32p refs

No abstract available.

25 A76-30859
OPTIMAL TRAJECTORIES OF HIGH-THRUST AIRCRAFT
Anderson, G.M. (USAF, Institute of Technology, Wright-Patterson AFB, Ohio) and Othling, W.L. (USAF, Aeronautical Systems Div., Wright-Patterson AFB, Ohio)
Journal of Aircraft, vol. 13, Mar. 1976, 180-184p

Future fighter aircraft may have sufficient thrust to sustain maximum-turn-rate flight at the corner velocity where the limits on the maximum lift coefficient and maximum normal-acceleration load factor are met simultaneously. Unfortunately, the usual necessary optimal control conditions break down on these corner velocity arcs. This paper presents a set of necessary optimality conditions which must hold when corner velocity arcs are part of an optimal aircraft trajectory. First, these necessary conditions are obtained for a general class of problems with two state dependent control variable inequality constraints. The resulting conditions

25 A76-30859 (Contd.)

are identical to those for optimal control problems with state variable inequality constraints. These necessary conditions then are applied to optimal trajectory problems with high-thrust aircraft. Two sample solutions to the problem of minimum time-to-turn through a specified heading angle are presented to illustrate some of the features of optimal trajectories with sustained maximum-turn-rate corner velocity arcs.

26 A76-26743
CONVERGENCE CONTROL IN DIFFERENTIAL DYNAMIC PROGRAMING APPLIED TO AIR-TO-AIR COMBAT
Jarmark, B.S.A. (Kungl. Tekniska Hogskolan, Stockholm; Saab Scania, AB, Linkoping, Sweden).
AIAA Journal, vol. 14, Jan. 1976, 118-121p, 7 refs.

An alternative to the step-size method is proposed for exercizing convergence control in the differential dynamic programming (DDP) technique applied to the computation of optimal trajectories for aircraft. The Bellman equation satisfied by the optimal cost function is given a first-order expansion. Convergence control is achieved with the aid of an extra penalty term to the function L under the integral in the cost functional. When the control vector contains at least one sensitive component that may cause wild trajectories, this component can be given a stronger penalty by the corresponding component in the diagonal matrix C contained in the extra penalty term. When stability has been reached, it is possible to increase the convergence rate by decreasing C carefully from iteration to iteration. First-order DDP and the new convergence control method were then tested on a known realistic air-to-air combat differential game, and efficiency of the new method was demonstrated.

27 A76-32627
ADVANCED FIGHTER CONTROL TECHNIQUES
Brinks, W.H. (McDonnell Aircraft Co. St. Louis, Mo.).
(Society of Experimental Test Pilots, Annual Symposium, 7th, Munich, West Germany, Apr. 24-26, 1975) Society of Experimental Test Pilots, Technical Review, vol.13. No. 1, 1976, 14-22p

A thirty flight investigation of the Control Configured Vehicle (CCV) design concept was conducted by McDonnell Aircraft Company (MCAIR) between June and August 1974. The test-bed aircraft was a Fly-by-Wire F14, modified with two shoulder-mounted, fully powered canard surfaces and wing leading edge slats. The thirty flight program consisted of performance and handling qualities investigations from near one hundred knots calibrated airspeed at 5000 feet to approximately 1.8 Mach at 35,000 feet. Longitudinal static margins varied from a positive 3% to a negative 7.5% Mean Aerodynamic Chord (MAC) with constant control system gains. The trim lift effect of the canard installation improved approach speeds by approximately seven knots and improved subsonic load factor available at constant angle of attack by approximately 25%. Short period disturbances resulted in dead beat damping in all axes for all configurations and static margins in the test envelope. Smooth aircraft response and lack of uncommanded motion at these conditions further indicated that CCV technology has significant operational potential.

28 N76-17156
SUMMARY OF FLIGHT TESTS TO DETERMINE THE SPIN AND CONTROLLABILITY CHARACTERISTICS OF A REMOTELY PILOTED, LARGE SCALE (3/3) FIGHTER AIRPLANE MODEL
Flight Research Center, Edwards, Calif.
Holleman, E.C.
NASA TN D - 8052 Jan, 1976

An unpowered, large, dynamically scaled airplane model was test flown by a remote pilot to investigate the stability and controllability of the configuration at high angles of attack. The configuration proved to be departure/spin resistant; however, spins were obtained by using techniques developed on a flight support simulator. Spin modes at high and medium-high angles of attack were identified, and recovery techniques were investigated. The results are compared with other scale model results. The remotely piloted systems and operational procedures are described.

29 A76-22282
DIGITAL FBW FLIGHT CONTROL AND RELATED DISPLAYS
Hooker, D.S. and Vetsch, G.J. (McDonnell Aircraft Co., St. Louis, Mo.)
Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, Culver City, Calif., Nov. 17-20, 1975, Paper 751041, 10p

An exploratory definition study has been conducted for an Advanced Fighter Digital Flight Control System. The principal objective was to derive and evaluate custom multimode control laws, related displays, and multichannel digital fly-by-wire implementation schemes for advanced Air Force and Navy fighters. Study results show that a triplex flight control system provides the lowest weight. the best maintainability, and the lowest cost of the candidate configurations considered. Results also indicate that mission-oriented flight control laws integrated with compatible displays and controllers can provide enchanced mission effectiveness and reduced pilot workload. It is recommended that the concepts analyzed and simulated during this definition study be implemented and evaluated by flight testing.

30 A76-22284
FLY-BY-WIRE FLIGHT CONTROL SYSTEM DESIGN CONSIDERATIONS FOR FIGHTER AIRCRAFT
Livingston, E.C. (General Dynamics Corp., Fort Worth, Tex.)
Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, Culver City, Calif. Nov. 17-20, 1975, Paper 751046. 9p.

The application of fly-by-wire flight control systems in fighter aircraft influences the basic design of the aircraft and requires special attention to certain design characteristics of the control system. The use of control-configured vehicles concepts for performance benefits makes fly-by-wire a logical choice. Redundancy management, protection against power loss, lightning protection and controller selection are prime design factors to be considered. Flight testing of the YF-16 aircraft has demonstrated excellent performance and operating characteristics of its fly-by-wire flight control system.

31 A76-22304
VECTORED LIFT ADVANCED FIGHTER TECHNOLOGY INTEGRATOR
Gibbons, T.A. and Ostroff, H.H. (McDonnell Aircraft Co., St. Louis, Mo.).
Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, Culver City, Calif. Nov. 17-20, 1975, Paper 751079, 19p. USAF supported research.

The paper presents the results of an advanced fighter technology integration study, which involved identification of high-payoff, mature technologies, the integration of these technologies into effective operational configurations, the design of manned demonstrator aircraft, and the validation of a selected concept through windtunnel tests and manned simulation. The Vectored Lift Fighter (VLF), employing new flight and control modes, was studied.. In the air-to-ground role, this advanced technology fighter/attack aircraft, when compared in sophisticated manned simulation with a baseline representative of the best current technology, killed one-and-a-half times as many targets while sustaining only one-fourth as many losses. In air-to-air engagements, it killed twice as many targets while sustaining one-sixth as many losses. Perhaps the most significant finding was that the effectiveness of fighter/attack aircraft employing these new flight and control modes cannot be properly assessed by traditional performance parameters.

32 A75-41651
DIGITAL FLIGHT CONTROL FOR ADVANCED FIGHTER AIRCRAFT
Gran, R., Berman, H., Rossi, M., and Rothschile, D. (Grumman Aerospace Corp., Bethpage, N.Y.)
American Institute of Aeronatuics and Astronautics, Guidance and Control Conference, Boston, Mass., Aug. 20-22, 1975, Paper 75-1086, 10p. 9 refs.

The operating characteristics of the next generation of fighter aircraft impose severe constraints which the control systems of these aircraft must overcome. The use of linear optimal digital control techniques allows one to answer some of the outstanding questions concerning how to design digital fly-by-wire control systems. By using an 'implicit model following' technique we have found that design specifications may be easily incorporated into the controller. By concentrating on noise and uncertainty we have found how to maximize the computer sample time, thereby reducing computer utilization. By appropriately incorporating all control surfaces we have found how to use these controls

32 A75-41651 (Contd.)

harmoniously to achieve the desired performance. Finally, all of these have been accomplished with a set of computer-aided design programs that are easily used and give rapid results. This paper describes the theoretical basis of our technqiues and its application to a typical 1980's advanced fighter aircraft.

33 A75-39520
FLUTTER INVESTIGATIONS ON A COMBAT AIRCRAFT WITH A COMMAND AND STABILITY AUGMENTATION SYSTEM
Lotze, A., Sensburg, O., and Kühn, M. (Messerschmitt-Bölkow-Blohm GmbH, Munich West Germany)
American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Meeting, Los Angeles, Calif., Aug. 4-7, 1975, Paper 75-1025, 13p 14 refs.

An analytical approach to the avoidance of instabilities in a sweepable-wing combat aircraft by means of an improved control system is presented. Based on a ground resonance survey, the elastic structure of the craft is described by normal modes; results of open and closed-loop calculations are given in Nyquist and common flutter plots and compared with flight test data.

34 N76-14018
THE EFFECTS OF BUFFETING AND OTHER TRANSONIC PHENOMENA ON MANEUVERING COMBAT AIRCRAFT
Advisory Group for Aerospace Research and Development, Paris (France)
Jul. 1975, 276p refs
(AGARD-AR-82)

A number of papers were presented dealing with various aspects of buffeting, and its effects on maneuvering combat aircraft. Some of the subjects discussed include operational problems at transonic speeds, human factors engineering, flow distribution at transonic speeds, dynamic response under buffeting conditions, stability and control, flight tests and wind tunnel techniques, and effects of configuration factors.

35 N76-14023
STABILITY AND CONTROL STATUS FOF CURRENT FIGHTERS
Air Force Flight Dynamics Lab., Wright Patterson AFB, Ohio.
Williams, W.G. and Lockenour, J.L. In AGARD The Effects of Buffeting and other Transonic Phenomena on Maneuvering Combat Aircraft Jul. 1975 45-53p

The current state-of-the-art of stability and control technology for maneuvering and precision tracking was discussed, including basic aerodynamics and aerodynamic stability and control flight control system concepts, and methods of prediction and analysis. It was shown that the maximum useable maneuvering capability of present fighter aircraft is often limited to 'g' levels below the maximum aerodynamic lift capability by stability, control and handling qualities degradations. In addition, handling qualities degradations often prohibit precision tracking although gross maneuvering may still be possible. Automatic flight control systems (stability augmentation and command augmentation) are being employed to correct many of the bare airframe deficiencies and additional capability is being provided by advancements in the fire control systems.

36 N76-14024
STABILITY AND CONTROL POTENTIAL FOR FUTURE FIGHTERS
Air Force Flight Dynamics Lab. Wright-Patterson AFB, Ohio
Lockenour, J.L., Williams, W.G. In AGARD The Effect of Buffeting and other Transonic Phenomena on Maneuvering Combat Aircraft) Jul 1975 54-62p

Advanced stability and control concepts aimed at further improving maneuvering and precision tracking were presented. The proposed new modes of control, methods of generating the required forces and moments necessary to produce the motions, flight control system concepts to implement the maneuvering modes, and the additional impact of pilot factors were discussed. Methods of prediction and analysis were also presented, and recommendations were made regarding the concepts and areas of analysis which are considered to be most important.

37 N76-14031
CONCLUSIONS AND RECOMMENDATIONS
Advisory Group for Aerospace Research and Development, Paris (France)
In its The effects of Buffeting and other Transonic Phenomena on Maneuvering Combat Aircraft Jul. 1975, 111-112p

General conclusions and specific recommendations on aircraft buffeting problems were presented. These include the need for (1) a total system analysis to determine the effects of buffeting during maneuvering flight (2) improved methods of viscous flow field and separation prediction, (3) comparing results from existing buffet onset prediction with wind tunnel and flight test data to determine their range of applicability, (4) better understanding of wind tunnel perturbation effects, (5) understanding of high speed stall progression, (6) identification of the interaction between the random aerodynamic driving forces and the structural response forces, (7) understanding the basic and interaction phenomena on existing and emerging fighters, and (8) isolating the effects of the various parameters more clearly, broadening the spectrum of the various parameters, and giving a better understanding of the physical process of buffeting.

38 N75-32096
FLUTTER SUPPRESSION AND STRUCTURAL LOAD ALLEVIATION
Advisory Group for Aerospace Research and Development, Paris (France)
Jul. 1975, 94p refs in English and partly in French Presented at the 40th meeting of the Struct. and Mater. Panel, Brussels, 13-18 Apr. 1975
(AGARD-CP-175)

Conference data on advances made in the area of flutter suppression and structrual load elleviation are summarized. Particular attention was given to system design, behavior, reliability, safety and redundancy, as found by analyses, model and flight tests. The use of active controls to suppress flutter was the dominant subject. The general problem was explored and specific examples and experiences were also presented. Flutter control of the wing/store combination, of the empannage and of a straight wing were studied, wind tunnel tests were discussed, automatic pilotage in turbulent air was examined and the mechanization of active controls was reviewed.

39 N75-32097
DESIGN CONSIDERATIONS FOR AN ACTIVE SUPPRESSION SYSTEM FOR FIGHTER WING/STORE FLUTTER
McDonnell Aircraft Co., St Louis, Mo.
Perisho, C.H., Triplett, W.E. and Mykytow, W.J. (AFFDL) In AGARD Flutter Suppression and Structural Load Alleviation, Jul. 1975, 19p, refs

Results from a previous study on wing/store flutter are extended in a preliminary system design to determine realistic system integration features, and to provide a feasibility evaluation of a completely automatic, pilot-out-of-the-loop, adaptive active flutter control system which automatically adjusts a system gain and compensation for different stores on the aircraft. Information obtained included a definition of details involving hydraulic and structural modifications, hardware and software components, flight safety features, expected performance benefits and limitations, and program plans for a wind tunnel verification effort and subsequent flight test demonstrations.

40 A75-37678
A DIGITAL FLIGHT MANAGEMENT SYSTEM CONCEPT FOR ADVANCED TACTICAL FIGHTER AIRCRAFT
Krippner, R.A. and Fenwick, C.A. (Rockwell International Corp., Collins Radio Group, Dallas, Tex). In: NAECON '75; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, June 10-12, 1975. (A75-37623 18-01)
New York, Institute of Electrical and Electronics Engineers, Inc., 1975 443-450p

A Digital Flight Management System (DFMS) is a 'front-end' organizing system for a number of major avionics systems onboard an aircraft. Not only are time-shared control/display techniques employed for reducing panel area requirements, but also the system eliminates a large portion of the tasks previously performed by the pilot while providing functional capabilities heretofore unavailable. Mission completion information is available after a single failure and flight critical information is available after two failures without resorting to mechanical back-up instrumentation. A significant aspect of the DFMS is the concept for fully automatic position fixing, flight plan management/steering, and a combined electronic chart, threat display and HSI.

41 A75-39823
THE PROPER SYMBIOSIS OF THE HUMAN PILOT AND AUTOMATIC FLIGHT CONTROL/
EIGHTEENTH LANCHESTER MEMORIAL LECTURE
Doetsch, K.H. (Braunschweig, Technische Universitat; Deutsche Forschungs- und
Versuchsanstalt fur Luft- und Raumfahrt, Braunschweig, West Germany).
Aeronautical Journal, vol. 79, June 1975, 247-260p 18 refs.

The basic characteristics of the phugoid theory are discussed, giving attention to its importance in connection with the development of STOL with high lift. Aspects of short period oscillations and autostabilization related to the extension of the flight regime to higher speed and higher altitude are examined. Problems related to human factors are considered along with the modern flight control concept and questions regarding the ideal form of cooperation between a future pilot and his aircraft control system.

42 N76-18112
INTERFACE OF FIGHTER THROTTLE/ENERGY MANAGEMENT FUNCTIONS WITH DAIS, FINAL
REPORT, 22 MAY 1974 - 30 APR. 1975
McDonnell Aircraft Co., St Louis, Mo.
Grose, G.G., Marsh, R.G. and Turner, R.D. Jun. 1975, 143p refs
(Contract F33615-74-C-3103, AF Proj. 2049)
(AD-A015804; AFFDL-TR-75-60)

A throttle/energy management (T/EM) concept for fuel, range, time optimization was extended by application to the Air Force Digital Avionics Information System (DAIS). The current state-of-technology of automatic throttle was reviewed considering features applicable to a T/EM system. The functional requirements of a T/EM system for fighter aircraft were defined, based on analysis of the aircraft characteristics and flight control system of the Advanced Development Program 680J configured F-4. Computational algorithms and control laws were developed by digital simulation. The T/EM system uses stored data for a limited set of optimal acceleration, dash and descent segments, from which the control commands and performance for a specific mission would be calculated.

43 N75-30027
IMPACT OF ACTIVE CONTROL TECHNOLOGY ON AIR-PLANE DESIGN
Advisory Group for Aeronautical Research and Development, Paris, (France)
Jun. 1975 318p refs in English and partly in French.
Presented at a Joint Symp. of the Flight Mech. Panel and Guidance and Control
Panel of AGARD-CP-157)

The papers are reported which were presented at sessions on active control technology in advanced airplane design, analysis and simulation programs, flight test programs, advanced flight control systems, and current operational systems. They cover a wide range of activities, from advanced research to systems in operation on the C-5A and Boeing 747 aircraft.

44 N75-30033
HORIZONTAL CANARDS FOR TWO-AXIS CCV FIGHTER CONTROL
Air Force Flight Dynamics Lab., Wright Patterson AFB, Ohio
Stumpfi, S.C. and Whitmoyer, R.A. In AGARD Impact of Active Control Technol.
on Airplane Design Jun. 1975, 8p, refs

The potential use is described of active horizontal canards in the design of fighter aircraft to provide flight path control along both the longitudinal and directional axes. The results are based on wind tunnel tests conducted on two CCV fighter configurations under the Fighter CCV Program of the USAF Flight Dynamics laboratory. A method for generating direct sideforce using differentially deflected horizontal canards is discussed. The direct lift control capabilities of horizontal canards are also presented. In addition, the use of horizontal canards in implementing the concepts of relaxed static stability and maneuver polar enhancement is described. Finally, the USAF Fighter CCV Program is outlined as it relates to demonstrating the performance improvements achievable through application of advanced control system technology.

45 N75-30034
ACTIVE CONTROL TECHNOLOGY: A MILITARY AIRCRAFT DESIGNER'S VIEWPOINT
Hawker Siddeley Aviation Ltd., Brough (England)
Melling, R. In AGARD Impact of Active Control Technol. on Airplane Design
Jun. 1975 16p

The most likely gains to be obtained by the application of active control technology to small combat aircraft are considered. There are seen to be considerable attractions, although the most significant benefits may turn out to be orientated towards the improved control and design freedom offered by ACT rather than towards revolutionary shapes or greatly increased efficiency or reduced weight. In the design of the ACS itself, it is considered essential that a mechanical back up is avoided in order to produce a more flexible, efficient and safe system, and to this end a suitably progressive system design philosophy must be developed. Despite some doubts as to the more ambitious claims for ACT, its ultimate adoption is expected for all but the simplest of aircraft.

46 N75-30036
CONTROL OF AN ELASTIC AIRCRAFT USING OPTIMAL CONTROL LAWS
Messerschmitt-Boelkow-Blohm G.m.b.H., Munich (West Germany)
Dressler, W. In AGARD Impact of Active Control Technol. on Airplane Design.
Jun. 1975, 11p

The design of a multivariable control system for gust alleviation is demonstrated. The use of computers for control design, summarized under the name computer aided design is described. The gust control system for gust alleviation is integrated into an overall flight guidance control system. Two control designs, using optimal control laws, are achieved, one with complete and the second with incomplete state measurement. In the model description the elastic behavior of the wing is included as well as the nonsteady aerodynamic lift generation and the dynamic behavior of the actuators. For a STOL-transport aircraft the efficiency of gust alleviation are shown in a flight through turbulent air. The increase of wing lifetime and the corresponding decrease in structure weight by use of a gust alleviation system is calculated.

47 N75-30037
CLOSED FORM EXPRESSION OF THE OPTIMAL CONTROL OF A RIGID AIRPLANE TO TURBULENCE
Office National d'Etudes et de Recherches Aerospatiales, Paris (France)
Coupry, G. In AGARD Impact of Active Control Technol. on Airplane Design
Jun. 1975, 10p refs in French; English summary

The flight of military aircraft at high speed, low altitude makes it necessary to use ride control systems to improve comfort, handling qualities and combat ability. The open loop system that is described senses turbulence which is used, after filtering, to act on the controls. Such a system does not change at all the handling qualities of the aircraft. Wiener's theory is used to derive in closed form the transfer function of the filter used for control. It is shown that this transfer function can be expressed in autoadaptative form, the poles being proportional to the velocity of the aircraft. The influence of parameters like mass, scale of turbulence, is discussed.

48 N75-30038
APPLICATION OF ADVANCED MODEL-FOLLOWING TECHNIQUES TO THE DESIGN OF FLIGHT CONTROL SYSTEMS FOR CONTROL CONFIGURED VEHICLES
Deutsche Forschungs- und Versuchsanstait fuer Luft- und Raumfahrt.
Oberpfaffenhofen (West Germany). Inst. Fuer Dynamik der Flugsysteme.
Hirzinger, G. In AGARD Impact of Active Control Technol. on Airplane Design
Jun. 1975, 15p, refs

After a review of optimal control, the model-following concept is applied for approaching a desired tracking behavior, especially concerning the airplane's response to a flight path angle command, in a systematic way. However, it turns out that the disturbance behavior of the controlled system, represented by the airplane's response to an initial deviation in the flight path angle, is unsatisfactory. Therefore a new concept combining model-following and partial state-vector feedback is applied for designing disturbance behavior and tracking behavior separately. In each of both cases achieving a good

48 N75-30038 (Contd.)

compromise between the desired system trajectory and limited control action. It appears that the control system thus designed is very insensitive to variations in the most critical parameter, that is the location of the center of gravity.

49 N75-30039
SURVIVABLE FLIGHT CONTROL SYSTEM: ACTIVE CONTROL DEVELOPMENT, FLIGHT TEST, AND APPLICATION
McDonnell Aircraft Co., St. Louis, Mo.
Krachmalnick, F.M., Berger, R.L. (AFFDL), Hunter, J.E., Morris, J.W. and Ramage, J.K. (AFFDL) In AGARD Impact of Active Control Technol. on Airplane Design.
Jun. 1975, 24p

The major portion of the Survivable Flight Control System (SFCS) Program initiated by the United States Air Force in July 1969 was performed to establish the practicality of active control concepts for use in future military aircraft. The SFCS quadruplex (four channel redundancy) primary flight control system is described. Incorporation of this type of control system in a tactical vehicle is expected to provide benefits in enhanced survivability, reliability, maintainability, cost of ownership, aircraft design freedom, and aircraft maneuvering performance. The simulations and ground-based system compatibility testing performed to verify equipment performance and establish high level of pilot confidence prior to flight, are discussed. A summary of the flight test results obtained during 84 successful flights is presented. Flight test results indicate that the F-4 with the SFCS installed exhibits greatly improved handling qualities over those characteristic of the production F-4. This aircraft incorporating control configured vehicle and maneuver load control conceptual features was successfully test-flown and evaluated. Results obtained from the pilot-in-the-loop simulations and actual flight tests are discussed. Flight test results verify that significant performance improvements in combat maneuvering envelope buffet levels, and specific excess power are achievable in the F-4 with judicious application of control configured vehicle concepts.

50 N75-30040
WEAPON DELIVERY IMPACT ON ACTIVE CONTROL TECHNOLOGY
Air Force Armament Lab., Eglin AFB, Fla
Smith, H. and Carleton, D. (AFFDL) In AGARD Impact of Active Control Technol. on Airplane Design.
Jun 1975, 14p refs

The need for cooperative efforts among the laboratories/test-organizations and users is emphasized to improve and properly match aircraft pointing and armament component accuracies to achieve the maximum effectiveness with conventional weapons. The Data Measurement Programs of the Armament Development and Test Center/Air Force Armament Laboratory are discussed, including the results and plans for the Instrumented Rack/Bomb and Gunnery Pipper/Fireline Trace and Impact Pattern Model Programs. The Active Control Technology Programs of the Air Force Flight Dynamics Laboratory including objectives, designs and results of the Tactical Weapon Delivery (TWeaD) Program are discussed. The objectives of the Multimode Control and the Control Configured Vehicle/Advanced Fighter Technology Integrator Programs are delineated. It is concluded that incorporation of active control technology and matched armament component accuracies in future weapon systems shows promise for considerable improvement in the effectiveness of unguided weapons.

51 N75-30042
A QUADRUREDUNDANT DIGITAL FLIGHT CONTROL SYSTEM FOR CCV APPLICATION
Messerschmitt-Boelkow-Blohm G.m.b.H., Munich (West Germany)
Kubbat, W.J. In AGARD Impact of Active Control Technol, on Airplane Design
Jun. 1975, 9p

A parallel redundant digital fly-by-wire system is described. It will be tested in the near future on a CCV-test aircraft (modified F-104 g). Starting from a fail-op, the reason for the choice of a digital system are outlined. The system works with freely programmable identical airborne computers which run identical software. The computers perform the control laws and act also as central voters and monitors. Basic of the design is the principle of majority decision with elimination of a failed component. Finally the Quadruplex system represents a functional integration of autopilot, stabilization, air data computation and built-in-test-equipment.

52 N75-30043
THE ASSET (ADVANCED SKEWED SENSORY ELECTRONIC TRIAD) PROGRAM
Naval Air Development Center, Warminster, Pa.
Abrams, C.R. and Weinstein, W.D. (Grumman Aerospace Corp.)
In AGARD Impact of Active Control Technol. on Airplane Design
Jun. 1975, 12p, refs

A redundant arrangement of angular rate sensors with skewed input axes, dispersed on an aircraft bulkhead, was designed for fly-by-wire control applications. Compared to other redundant configurations, it best satisfied system reliability, survivability, and maintenance requirements. By also utilizing a high reliability solid-stat angular rate sensor, expected maintenance costs will be decreased. The data management system designed for the ASSET configuration featured a parallel path failure detection and isolation algorithm. A unique method of selecting failure thresholds was developed to insure that false alarm probability and system errors were minimized. The results of this effort will contribute to the practical implementation of a digital fly-by-wire system, since a successful attempt was made to match proposed operational requirements. The ASSET concept will therefore provide a fail-operational and combat-survivable set of rate sensors designed to interface with all active control systems, regardless of redundancy requirements.

53 N75-30044
THE RELEVANCE OF EXISTING AUTOMATIC FLIGHT CONTROL SYSTEMS TO THE FUTURE DEVELOPMENT OF ACTIVE CONTROL
Marconi-Elliott Avionic Systems Ltd., Rochester (England) Flight Control Div.
Ruggles, R., Sweeting, D. and Watson, I.A. In AGARD Impact of Active Control Technol. on Airplane Design
Jun. 1975, 15p refs

Some relevant examples of failure-survival automatic flight control systems are examined to show how the results of their design, implementation and operational usage can contribute to the successful introduction into full-time use of active control technology (ACT). Ground rules which were evolved some years ago for such redundant systems are re-examined in the interest of full-time ACT. The important parameters affecting the successful design of a full-time ACT system are discussed. Some of the problem areas are mentioned and the use of some existing techniques for successful certification are suggested. The step from current fail-operative systems relying on some reversionary system to full-time ACT is examined. The design requirements for the hardware and software for digital computations are detailed and some special problems of digital systems are highlighted and solutions are suggested. Some of the problems of system components such as sensors, computers and actuators are discussed.

54 N75-30048
THE HUNTER FLY-BY-WIRE EXPERIMENT: RECENT EXPERIENCE AND FUTURE IMPLICATIONS
Royal Aircraft Establishment, Farnborough (England). Flight Systems Dept.
Gill, F.R. and Fullham, P.W.J. In AGARD Impact of Active Control Technol. on Airplane Design
Jun. 1975, 12p refs

The impact of active control technology on the design of future aircraft depends on the development of full-time and full authority control systems which have an integrity similar to that of the basic airframe. One of the major items of the R and D Programme in the UK which is aimed at providing this flight experience with the system is described. The implications of the future application of active control technology are discussed in terms of the airworthiness problem; and the manner of designing systems so as to ease the certification of high integrity, full-time and full authority control.

55 N75-30049
F-8 DIGITAL FLY-BY-WIRE FLIGHT TEST RESULTS VIEWED FROM AN ACTIVE CONTROLS PERSPECTIVE
National Aeronautics and Space Administration. Flight Research Center, Edwards, Calif.
Szalai, K.J. and Deets, D.A. In AGARD Impact of Active Control Technol. on Airplane Design
Jun. 1975, 14p refs

The results of the NASA F-8 digital fly-by-wire test program are presented, along with the implications for active control applications. The closed loop performance of the digital control system agreed well with the sampled-data system design predictions. The digital fly-by-wire mechanization also met pilot flying qualities requirements. The advantages of mechanizing the control laws in software became apparent during the flight program and were realized without sacrificing overall system reliability. This required strict software management. The F-8 flight test results are shown to be encouraging in light of the requirements that must be met by control systems for flight-critical active controls applications.

56 N75-30051
THE C-5A ACTIVE LIFT DISTRIBUTION CONTROL SYSTEM
Lockhead-Georgia Co., Marietta
Grosser, W.F., Hollenbeck, W.W. and Eckholdt, D.C. In AGARD Impact of Active Control Technol. on Airplane Design.
Jun. 1975, 18p, refs

The technical details are presented of the development of the Active Lift Distribution Control System (ALDCS) for the C-5A aircraft. A structural loads, and flutter-control system interaction are developed in such a way that the unique aspects of the analysis, aeroelastic wind tunnel test, and flight test portion are bound together to indicate the system design characteristics performance. The purpose of the ALDCS is to reduce gust and maneuver incremental wing root bending moments while minimizing the effects of the control system on torsion, flutter, and flying qualities. These criteria are based on axial load reduction as a means of improving wing fatigue endurance without significantly affecting existing flutter margins or handling qualities. Even though this is a retrofit system which was required to use as much exisitng hardware as possible, throughout the flight test all design goals were met. The system is currently planned to be manufactured and installed on the fleet during the next several years.

57 A75-42175
APPLICATIONS OF ELECTRONIC PROCESSORS TO THE OPERATIVE CONTROL OF AIRCRAFT (APPLICAZIONE DEGLI ELABORATORI ELETRONICI ALLA CONDOTTA OPERATIVA DEI VELIVOLI)
Finocchio, P. Rivista Aeronautica, vol. 51, May-June 1975, 105-116p
In Italian

This paper examines a general scheme for the acquisition, processing, and reacting to external data on the basis of which flight plans, navigational calculations, and profiles of attack are decided in flight, and then discusses the role that electronic processors would play in such a scheme. The general features of an integrated avionics system are described.

58 N76-14141
FLIGHT INVESTIGATION OF FIGHTER SIDE-STICK FORCE-DEFLECTION CHARACTERISTICS
Final Report, Sep. 1974-May 1975
Galspan Corp., Buffalo, N.Y.
Hall, G.W. and Smith, E.
May 1975, 94p refs (Contract F33615-73-C-3051: AF Proj. 8219)
(AD-A013926: CALSPAN-AK-5280-F-8; AFFDL-TR-75-39)

A flight investigation of fighter side-stick controller force-deflection characteristics was performed using the USAF NT-33A variable stability airplane equipped with a variable feel side stick. The simulated airplane and control system characteristics were representative of a modern high performance fighter employing a side-stick controller. Up-and-away tasks including formation, air-to-air tracking and acrobatic maneuvering, and landing approach tasks were evaluated by two pilots. Four values of nonlinear pitch and roll side-stick force-command gain resulting in different response per force ratios were evaluated with different side stick force-deflection gradients, including a rigid side stick.

59 A75-33615
YF-16 - A RARE OPPORTUNITY
Oestricher, P.F. (General Dynamics Corp., Convair Aerospace Div., San Diego, Calif.)
Society of Experimental Test Pilots, Technical Review, vol. 12, no. 3, 1975, 22-26p

A pilot's report is presented on the testing of the YF-16 fighter aircraft and on the characteristics of the craft itself. The principal systems of the fighter are discussed.

60 N75-16560
ANALYSIS OF LONGITUDINAL PILOT-INDUCED OSCILLATION TENDENCIES OF YF-12 AIRCRAFT
National Aeronautics and Space Administration. Flight Research Center, Edwards, Calif.
Smith, J.W. and Berry, D.T. Washington Feb. 1975 40p refs
(NASA-TN-D-7900; H-805)

Aircraft flight and ground tests and simulator studies were conducted to explore pilot-induced oscillation tendencies. Linear and nonlinear calculations of the integrated flight control system's characteristics were made to analyze and predict the system's performance and stability. The investigations showed that the small-amplitude PIO tendency was caused by the interaction of the pilot with a combination of the aircraft's short-period poles and the structural first bending mode zeros. It was found that the large-amplitude PIO's were triggered by abrupt corrective control actions by the pilot, which caused the stability augmentation system servo to position and rate limit. The saturation in turn caused additional phase lag, further increasing the tendency of the overall system to sustain a PIO.

61 A75-37135
DIGITAL ADAPTIVE FLIGHT CONTROL DESIGN USING SINGLE STAGE MODEL FOLLOWING INDICES
Alag, G. and Kaufman, H. (Rensselaer Polytechnic Institute, Troy, N.Y.).
In: Conference on Decision and Control, 5th and Symposium on Adaptive Processes, 13th, Phoenix, Ariz., November 20-22, 1974, Proceedings. (A75-37134) New York, Institute of Electrical and Electronics Engineers, Inc., 1974, 122-127p, 11 refs.
Grant No. NGR-33-018-183

Simple mechanical linkages are often unable to cope with many control problems associated with high-performance aircraft. This has led to the development of digital fly-by-wire control systems and in particular digital adaptive controllers that can be efficiently adjusted during system operation. To this effect, a control law has been derived based upon the minimization of a single-stage weighted combination of control energy and the squared error between the states of a linear plant and model. This control logic is interfaced with an on-line weighted least-squares estimator and a Kalman state filter. The utility of the resultant control system is illustrated by its application to the linearized dynamics of a typical fighter aircraft.

62 A75-22940
F-4/CCV-FLIGHT TESTS OF ADVANCED TECHNOLOGY
Bennett, D.H. (McDonnell Aircraft Co., St. Louis, Mo.)
Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, San Diego, Calif., Oct. 1-3, 1974, Paper 740861, 9p.

Previous studies indicated the F-4 fly-by-wire (surfaces controlled by electrical signals rather than by mechanical inputs) aircraft to be a good test bed for flight tests of advanced concepts. In particular, the advanced technology control configured vehicle (design for control, rather than stability, in initial design phase) concepts of a short-coupled horizontal canard (control surface forward of the wing) and relaxed static longitudinal stability were shown to have large performance benefits for maneuvering flight conditions in the combat arena. The short-coupled canard has slat-like favorable interference effects on the wing lift and drag characteristics, regardless of whether leading edge slats are or are not installed on the wing. Development of the company-sponsored precision aircraft control technology aircraft to flight status was not without challenges, but these were satisfactorily met. Flight tests have verified the predicted performance benefits, while providing additional reliability/maintainability data on fly-by-wire control systems.

63 A75-22939
AFTI TI-1 PROGRAM
Haas, R.L., O'Connor, W.M., Fraga, D.E. (USAF, Systems Command, Andrews AFB, Washington, D.C.)
Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, San Diego, Calif, Oct. 1-3, 1974, Paper 740860. 14p

The advanced fighter technology integration (AFT) program is a concept for accelerating the transition of high payoff technologies through the development stage into systems application. Attention is given to the four phases of the first program to incorporate the AFTI approach. The development of advanced controls is considered along with a high-acceleration cockpit, advanced composites, drag modulation, a technology options study, aspects of design efficiency, system effectiveness, total system cost, alternate capability enhancement, and configuration selection.

64 A75-17832
EXPLICIT FORM OF THE OPTIMAL CONTROL LAW FOR A RIGID AIRCRAFT FLYING IN A TURBULENT ATMOSPHERE (FORME EXPLICITE DE LA LOI OPTIMALE DE PILOTAGE D'UN AVION RIGIDE VOLANT EN ATMOSPHERE TURBULENTE)
Coupry, G. (ONERA, Chatillon-sous-Bagneux, Hauts-de-Seine, France).
(NATO, AGARD, Symposium on Impact of Active Control Technology on Airplane Design, Paris, France, Oct. 13-18, 1974) ONERA, TP no. 1412, 1974, 11p, 6 refs. In French.

Closed-loop ride control systems, which feed back, after appropriate filtering, certain aircraft responses (such as pitch speed) to the control surfaces, are widely used in designing high-speed, low-altitude military aircraft. The article explains how Wiener's theory makes it possible to derive the optimal control law explicitly as a function of reduced parameters which are directly dependent not on speed, but on the aircraft power-to-weight characteristics, dimensionless lift and moment coefficients, air density, and turbulence. The system proposed is an open-loop system which give commands to the control surfaces depending only on the turbulence encountered, which is measured in real time on board the aircraft. Such a control system has been installed on a Mirage III for flight testing.

65 A75-24140
PROBLEMS AND IMPLEMENTATION POSSIBILITIES OF A DIRECT SIDE FORCE CONTROL IN THE CASE OF FIGHTERS (PROBLEMATIK UND REALISIERUNGSMOGLICHKEITEN EINER DIREKTEN SEITENKRAFTSTEUERUNG BEI KAMPFFLUGZEUGEN)
Benner, W. and Wunnenberg, H. (Dornier GmbH, Friedrichshafen, West Germany).
Deutsche Gesellschaft fur Luft- und Raumfahrt, Jahrestagung, 7th Kiel, West Germany, Sept. 17-19, 1974, Paper 74-84, 43p, 10 refs. In German.
Bundesministerium der Vertiedigung Contract No. TR-720-R-7600-42-009

Questions concerning the generation of the forces needed for a lateral acceleration are examined, taking into account the effect of the forces on aircraft dynamics. The main problem is related to the compensation of perturbation moments. Simple control principles which can be implemented without complex control requirements will apply in the case of a suitable design of the direct side force control with regard to the control surfaces. It is, therefore, possible to obtain direct side force control in the case of ordinary fighters without stabilization devices.

66 A74-37810
ESTIMATION OF NONLINEAR AERODYNAMIC DERIVATIVES OF A VARIABLE GEOMETRY FIGHTER AIRCRAFT FROM FLIGHT DATA
Ramachandran, S and Wells, W.R. (Cincinnati, University, Cincinnati, Ohio).
American Institute of Aeronautics and Astronautics, Mechanics and Control of Flight Conference, Anaheim, Calif., Aug. 5-9, 1974, Paper 74-790, 11p, 13 refs
Grant No. NGR-36-004-061

This paper is concerned with the estimation of stability and control parameters of high performance fighter aircraft from data obtained from high angle of attack flight. The estimation process utilizes a maximum likelihood algorithm derived for the case of a nonlinear aerodynamic force and moment model. The aircraft used was a high speed variable sweep heavy weight fighter with twin vertical tails. Comparisons of results from the nonlinear analysis are made with linear theory and wind tunnel results when available.

67 A74-37811
STATUS OF DESIGN CRITERIA FOR PREDICTING DEPARTURE CHARACTERISTICS AND SPIN SUSCEPTIBILITY
Weissman, R. (USAF, Aeronautical Systems Div., Wright-patterson AFB, Ohio)
American Institute of Aeronautics and Astronautics, Mechanics and Control of Flight Conference, Anaheim, Calif., Aug. 5-9, 1974, Paper 74-791, 8p, 13 refs.

The most familiar criteria for predicting aircraft departure characteristics and spin susceptibility are based on lateral-directional static stability parameters. Data correlating the criteria with experimental results for several aircraft are considered. It is found that the criteria currently in use can be employed with a reasonable degree of confidence during preliminary design. The analysis suggested by Larson (1973) for predicting lateral-directional stability characteristics shows considerable promise. However, there are also some drawbacks.

68 A74-41803
AN INVESTIGATION OF OVERALL SYSTEMS CRITERIA FOR THE LONGITUDINAL FLYING QUALITIES OF HIGHLY AUGMENTED FIGHTER AIRCRAFT
Chen, R.T.N. and Boothe, E.M. (Calspan Corp., Buffalo, N.Y.)
American Institute of Aeronautics and Astronautics, Mecahnics and Control of Flight Conference, Anaheim, Calif., Aug. 5-9, 1974 Paper 74-833, 11p, 13 refs.
Contract No. F33615-73-C-3051

A longitudinal control system design procedure based on previously developed design criteria, including those of MIL-F-8785B and suggested revisions to MIL-F-8785B, was developed. Four separate flight control systems were designed using combinations of normal acceleration, change in angle of attack and pitch rate feedback with constant gains and a forward loop gain scheduled with dynamic pressure. The USAF variable stability NT-33A airplane was used as a flight test vehicle to evaluate each of the four systems. The NT-33A was augmented by its variable stability system to simulate the characteristics of a typical unaugmented, high-performance fighter aircraft. The control systems to be evaluated were mechanized around the simulated airplane. The results of the flight test showed that all four of the flight control systems provided satisfactory flying qualities for the flight phases evaluated.

69 A74-37868
DIGITAL ADAPTIVE MODEL FOLLOWING FLIGHT CONTROL
Alag, G.S. and Kaufman, H. (Rensselaer Polytechnic Institute, Troy, N.Y.)
American Institute of Aeronautics and Astronautics, Mechanics and Control of Flight Conference, Anaheim, Calif., Aug. 5-9, 1974, Paper 74-886, 8p, 11 refs
Grant No. NGR-33-018-183

Sample mechanical linkages are often unable to cope with the many control problems associated with high performance aircraft maneuvering over a wide flight envelope. One procedure for retaining uniform handling qualities over such an envelope is to implement a digital adaptive controller. Towards such an implementation an explicit adaptive controller, which makes direct use of online parameter identification, has been developed and applied to the linearized equations of motion for a typical fighter aircraft. The system is composed of an online weighted least squares identifier, a Kalman state filter, and a single stage real model following control law. The corresponding control gains are readily adjustable in accordance with parameter changes to ensure asymptotic stability if the conditions for perfect model following are satisfied and stability in the sense of boundedness otherwise.

70 A74-38249
MANAGEMENT OF ANALYTICAL REDUNDANCY IN DIGITAL FLIGHT CONTROL SYSTEMS FOR AIRCRAFT
Montgomery, R.C. and Price, D.B. (NASA, Langley Research Center, Flight Dynamics and Control Div., Hampton, Va.)
American Institute of Aeronautics and Astronautics, Mechanics and Control of Flight Conference, Anaheim, Calif., Aug. 5-9, 1974, Paper 74-887, 11p.

This paper presents a design method for optimal redundancy management for nonlinear systems with application to highly maneuvering aircraft. The approach taken is based on selecting the failure states to be covered by the system design and

70 A74-38249 (Contd.)

constructing a cost function that represents the cost of making an incorrect decision. The decision logic which minimizes the cost requires a bank of extended Kalman filters running in parallel. This produces a severe computational requirement. To reduce this requirement, a suboptimal logic is developed based on using a nonlinear single-stage prediction algorithm in the filters with filter gains and decision logic selected using steady-state results obtained from a linearization of the vehicle and sensor dynamics. The design process is then applied to designing a redundancy management system for the F8-C aircraft. Results indicate that the system is superior in failure detection to a system using the same structure but using a linear single-stage prediction algorithm in the filters.

71 A74-37893
A CLASSICAL APPROACH TO THE DESIGN OF MODEL-FOLLOWING CONTROL SYSTEMS
Motyka, P.R. (Calspan Corp., Buffalo, N.Y.)
American Institute of Aeronautics and Astronautics, Mechanics and Control of Flight Conference, Anaheim, Calif., Aug. 5-9 1974, Paper 74-913, 10p, 6 refs.
Contract No. N62269-73-C-0937

This paper presents the development of a classical design technique for determining feedback gains which lessen the sensitivity of model-following flight control systems to parameter variations. The gains are chosen to achieve suitable stable closed-loop poles as defined by parameters such as frequency damping bandwidth, etc. A model-following flight control system for a fighter aircraft is designed to demonstrate the technique. A brief development of linear model-following theory is presented. The design of both the longitudinal and lateral-directional feedback systems using the classical approach is considered. The use of sideslip angle feedback and y-direction acceleration feedback for the lateral-directional system are contrasted. Time histories of the model and plant responses are compared throughout to demonstrate the validity of the design technique.

72 N75-24757
DIGITAL FLIGHT CONTROL SYSTEM FOR TACTICAL FIGHTERS Final Report, Feb. 1972 - Dec. 1973
Honeywell, Inc., Minneapolis, Minn. Systems and Research Center.
Konar, A.F., Gaabo, R.J., Bender, M.A., Smith, F.L. and Wolf, J.D. Jul. 1974, 424p
(Contract F33615-72-C-1058; AF Proj. 1987)
(AD-A002686; F0121-IR1; AFFDL-TR-74-69)

The Digital Flight Control Systems for Tactical Fighters Program is a development program the objective of which is to define the technology necessary to apply digital flight control techniques to the three-axis, multiple flight control configuration demands of advanced fighter aircraft. Analysis efforts have defined powerful analytical DF CS models and computer program tools which permit determination of flight control system performance as a function of computational parameters -- word length, sample rate, and computational delays. An exercise of the programs using the F-4 as a model indicated 100 iterations per second as satisfactory for the longitudinal axis. For Vol. 11, see N75-20349

73 N75-20348
DIGITAL FLIGHT CONTROL SYSTEM FOR TACTICAL FIGHTER, VOLUME 1: DIGITAL FLIGHT CONTROL SYSTEM ANALYSIS Interim Report, Feb 1972 - Jun. 1973
Honeywell, Inc., Minneapolis, Minn. Systems and Research Center.
Ferit Konar, A., Mahesh, J.K and Kizilos, B. Jun. 1974, 353p refs
(Contract F33615-72-C-1058; AF Proj. 1987)
(AD-A002320; F0131-IR1-Vol-1; Honeywell-08001-Vol-1; AFFDL-TR-73-119-Vol-1)

The Digital Flight Control for Tactical Fighters Program is a development program which defines the technology necessary to apply digital flight control techniques to the three-axis, multiple flight control configuration demands of advanced fighter aircraft. Analysis efforts to date have defined powerful computer program tools which permit determination of flight control system performance as a function of computational parameters -- word length, sample rate, and computational delays. An exercise of the programs using the F-4 as a model indicates 100 iterations per second as satisfactory for the longitudinal axis.

74 N75-20349
DIGITAL FLIGHT CONTROL SYSTEMS FOR TACTICAL FIGHTERS. VOLUME 2: DOCUMENTATION OF THE DIGITAL CONTROL ANALYSIS SOFTWARE (DIGIKON) Interim Report, Feb. 1972 - Oct. 1973.
Honeywell, Inc., Minneapolis. Minn. Systems and Research Center.
Konar, A.F., Kizilos, B., Gayl, J., Mahesh, J.K. and Borow, M.
Jun. 1974, 478p refs
(Contract F33615-72-C-1058; AF Proj. 1987)
AD-AOO 2327; FO 131-IR1-Vol.2; Honeywell-08001. Vol.2; AFFDL-TR-73-119-Vol.2

The computer programs which implement the mathematical analyses and models developed in Volume 1 are described. The programs are developed in Fortran IV language. Extensive use of subroutines is made to provide programming flexibility when considering alternate airframe/dynamics/control points/measurement systems/ controllers effect on control system performance. A demonstration example is included in Volume 1 to illustrate how these programs are used and how the computational requirements are derived.

75 N75-24754
DIGITAL FLIGHT CONTROL SYSTEMS FOR TACTICAL FIGHTERS. VOLUME 3. DIGITAL FLIGHT CONTROL SYSTEM DESIGN CONSIDERATION Interim Report. Feb. 1972 - Jun. 1973
Honeywell, Inc., Minneapolis, Minn. Government and Aeronautical Products Div.
Bender, M.A., Gaabo, R.J., and Smith, F.L.
Jun. 1974, 436p (Contract F33615-72-C-1058; AF Proj. 1987)
(AD-A002687; GAPD-F-0131-IR3; AFFDL-TR-73-119-Vol.3)

For abstract, see Item 72

76 A74-39888
FLY-BY-WIRE - WHAT DOES IT WEIGH
Ross, G.E. (McDonnell Aircraft Co., St Louis, Mo.).
Society of Allied Weight Engineers, Annual Conference, 33rd, Fort Worth, Tex., May 6-8, 1974, Paper 1018, 17p USAF - sponsored research.

An evaluation is made of the weight of fly-by-wire (FBW) flight control systems for advanced fighter aircraft. The evolution of flight control system weight is traced from a manual system through varying levels of hydraulic boost and augmented power controls, to complete FBW. Projected weight trends of future control systems reveal the possibility of achieving a lighter flight control system.

77 N74-31458
AIRCRAFT DESIGN INTEGRATION AND OPTIMIZATION, VOLUME 1.
Advisory Group for Aerospace Research and Development, Paris (France)
Jun. 1974, 347p refs in English; partly in French Conf. held at Florence, Italy 1-4 Oct. 1973.
(AGARD-CP-147-Vol.1)

The proceedings of a conference on aircraft design integration and optimization are presented. The subjects discussed include the following: (1) the preliminary design process and its impact on cost, (2) methods and approaches for balancing requirements, capabilities, and costs in aircraft design, (3) analysis, optimization, and validation testing techniques, and (4) the integration of subsystems and application of new technology.

78 N74-31483
ADVANCEMENTS IN FUTURE FIGHTER AIRCRAFT
Messerschmitt-Boelkow-Blohm G.m.b.H., Munich (West Germany)
Herbst, W. In AGARD Aircraft Design Integration and Optimization, Vol.1
Jun. 1974, 7p refs

An analysis of advanced design technology as applied to future fighter aircraft was conducted. The following conclusions were reached: (1) a new aircraft development can be justified if the performance of the new aircraft exceeds that of the old by 15 to 20 percent. (2) foreseeable technological air frame advances, such as CCV and composites, do not justify the development of new weapon systems, per se. (3) refent engine technology advances allows a performance improvement which will justify new aircraft design, and (4) foreseeable air frame advances will pay off if applied to new aircraft development.

79 A74-38551
A DIGITAL MULTIMODE FLIGHT CONTROL SYSTEM FOR TACTICAL FIGHTERS
Bassett, K and Yechout, T. (Honeywell, Inc., Minneapolis, Minn.).
In: NAECON '74; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 13-15 1974. (A74-38517) New York, Institute of Electrical and Electronics Engineers, 1974, 300-307p.

Review of program for the development of a digital multimode flight control system aimed at a flight test evalution on an A-7D tactical aircraft. Among the achievements to be realized by the program are: (1) the validation of computation parameter requirements for tactical aircraft; (2) flight evaluations of digital multimodes usable for weapons delivery missions; (3) real-world testing of redundancy and self-test concepts; and (4) experience in soft-ware validation and control for digital flight control systems. Each of these achievements is expected to result in appreciable benefits for future advanced flight control applications.

80 N74-31429
ADVANCES IN CONTROL SYSTEMS
Advisoty Group for Aerospace Research and Development, Paris (France)
May 1974, 313p refs in English partly in French Conf. Presented at 17th Meeting of the Guidance and Control Panel of AGARD, Geilo, Norway, 24-26 Sep. 1973.
(AGARD-CP-137)

The proceedings of a conference on control systems for aircraft control, engine control, and automatic pilots are presented. The subjects discussed include the following: (1) applied control theory, (2) control system performance optimization, (3) control system architecture and reliability, (4) application of advanced control systems, and (5) integrated flight control and operations. The characteristics of control systems for specific types of aircraft are analyzed. The development and application of fly by wire techniques are reported. The use of computers as an aid to flight control system design is explained.

81 N74-31431
THE DIGITAL AIRPLANE AND OPTIMAL AIRCRAFT GUIDANCE
Office of the Assistant Chief of Staff (Air Force) Washington, D.C.
Dayton, A.D. In AGARD Advan. in Control Systems May 1974, 14p refs

The use of optimal flight path guidance for aircraft in satisfying various military and civilian mission requirements is discussed. The concepts, systems, and algorithms which make optimal aircraft flight path guidance feasible are presented. The digital airplane which is based on a large digital computation capability, a digital data bus, sensors, and display systems is used as an example. The development of the methodology and algorithms for directing the aircraft is investigated.

AD-A041 967 ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT--ETC F/G 5/8
TASK-ORIENTED FLIGHT CONTROL SYSTEMS.(U)
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82 N74-31432
SOME INTEGRITY PROBLEMS IN OPTIMAL CONTROL SYSTEMS
Norges Tekniske Hoegskole, Trondheim
Solheim, O.A. In AGARD Advan. in Control Systems May 1974, 10p refs

A multivariable feedback control system is defined as being of high integrity if it remains stable under failure conditions. Integrity problems encountered in optimal control systems are investigated. Two types of failure conditions are considered, namely actuator failure and sensor failure. As to the structure of the controlsystem, a linear feedback law with feedback from all the state variables is considered. Systems with state estimators are also dealt with. The integrity problem is discussed based on the eigenvalues of the closed-loop system. Some design procedures are suggested. Finally, some numerical results are presented.

83 N74-31433
APPLICATION OF MODAL CONTROL THEORY TO THE DESIGN OF DIGITAL FLIGHT CONTROL SYSTEMS
Bodenseewerk Geraetetechnik G.m.b.H., Ueberlingen (West Germany)
Hartmann, U. In AGARD Advan. in Control Systems May 1974 21p, refs

The design of digital flight control systems is substantially simplified by using modal design methods. The theory of modal design is based on a state space description of the control system. For a desired pole distribution of the control system this theory directly provides a gain matrix for the feedback of the state variables. Due to the fact that all state variables are not always available, the problem of estimating non-measurable state variable arises. For solving this problem the theory of observers can be used. It shows however that an observer is not in a position to provide without adaptation usable estimated values of the missing state variables for the complete flight range. For solving practical design problems a minimum order observer is therefore particularly suitable as it is generally easier to obtain programmable approximation laws for the small number of parameters of this observer. It was further attempted to circumvent the estimation problem by the following means: (1) simplification of the state equations to eliminate non-measureable state variables, (2) transformation of the state vector and, (3) appropriate selction of the desired pole distribtuion. It showed that in this way a prompt and direct design of discrete-time flight control systems is possible. Two examples are used to demonstrate the results of simulations and flight tests: The design of a pitch attitude control system and a roll/yaw control system for a STOL aircraft.

84 N74-31435
A DESIGN PROCEDURE UTILIZING CROSSFEEDS FOR COUPLED MULTILOOP SYSTEMS
Air Force Avionics Lab., Wright Patterson AFB, Ohio
Basile, P.S. and Curry, R.E. (MIT Cambridge) In AGARD Advan. in Control Systems May 1974, 10p, refs.

A frequency domain design procedure for decoupling multi-input, multi-output systems is described; the frequency domain has the advantage of providing insight and ease of satisfying specifications that are difficult to meet with state-space methods. A design procedure for a two-input, two-output system without crossfeeds is presented first; crossfeeds are then introduced to alter the open loop dynamics, and the design procedure is applied to the modified plant. The constraints on the choice of crossfeeds are discussed. Extension to a two-input, three-output system is made when one of the outputs is dominated by another; guidelines for choosing the crossfeeds are given. This procedure is applied to design a lateral cruise control system for the space shuttle orbiter; exact decoupling with crossfeeds result in excellent closed loop response.

85 N74-31436
CONSTRUCTION OF SUBOPTIMAL KALMAN FILTERS BY PATTERN SEARCH
Norwegian Defence Research Establishment, Kjeller. Div. for Electronics
Christophersen, N. and Lange-Nielsen, T. In AGARD Advan. in Control Systems
May 1974, 6p, refs

A systematic method for the optimal determination of parameters in suboptimal Kalman filters is presented. Such simplified filters are frequently necessary in order to implement a Kalman filter on a small special purpose computer. In order to optimize the performance of these filters, a parameter optimization problem may be involved. The method of solution is a modified version of Rosenbrock's pattern search. This is a direct search, permitting a very wide class of performance measures not necessarily analytical in nature. The example given is the determination of a suboptimal filter for a hybrid marine navigation system with thirty state variables.

86 N74-31437
USE OF ADVANCED CONTROL THEORY AS A DESIGN TOOL FOR VEHICLE GUIDANCE AND CONTROL
Singer Co., Little Falls, N.J. Kearfott Div.
Brodie, P.M. In AGARD Advan. in Control Systems
May 1974, 10p.
Contract F08635-71-C-0227

A technique is demonstrated which permits the numerical solution of the linear optimal regulator problem to be used as a generalized design tool. In particular this technique affords simplification over the usual frequency domain methods for high order guidance and control systems while retaining compatibility with the frequency domain especially for stability analysis. In addition to making a more rapid solution to the design problem possible, the structure of the optimal controller lends itself to the combination of the guidance and control problems into a single optimum or best solution.

87 N74-31439
FLIGHT CONTROL SYSTEM DEVELOPMENT IN THE UK
Royal Aircraft Establishment, Farnborough (England). Avionics Dept.
Kimberley, D and Fullam, P.W.J. In AGARD Advan. in Control Systems
May 1974, 13p, refs.

The development of automatic flight control systems in the U.K. is described. Military and civilian applications of control system development are reported. The requirements of a control system are defined with respect to mission performance, system integration, similar redundancy, and control actuation. Specific examples of control installation and flight test results are included. The flight test results indicate that a full time fly by wire system is feasible and represents a prerequisite to system exploitation in the form of such concepts as control configured vehicles.

88 N74-31442
ON THE DESIGN AND EVALUATION OF FLIGHT CONTROL SYSTEMS
Royal Aircraft Establishment, Farnborough (England). Controls and Displays Div.
Gill, F.R. In AGARD Advan. in Control Systems
May 1974, 13p, refs

An analysis of flight test results of control systems for fighter and transport aircraft is presented. The systems under consideration employ conventional linear control policies with the design being based on a parameter optimization technique. The two modes which are discussed are a pitch rate maneuver demand system for the fighter aircraft and an ILS glide path and flare system for the transport aircraft. Studies to replace linear control by variable gain policies are discussed. The reasons for and the principles of the variable gain control policies are outlined. The principles of flight evaluation methods employed with the control system tests are included.

89 N74-31444
DEFINITION AND SIMULATION OF A DIGITAL FILTER AND PILOT DEVICE UTILIZING MODERN DESIGN TECHNIQUES OF FILTRATION CONTROL (DEFINITION ET SIMULATION D'UNE BOUCLE DIGITALE DE PILOTAGE D''ENGIN UTILISANT LES TECHNIQUES MODERNES DE FILTRAGE ET DE COMMANDE)
Laboratoire Central de Telecommunications, Paris, (France)
Darmon, C.A. and Euzen, H. In AGARD Advan. in Control Systems
May 1974, 13p, refs in French

Modern optimal control techniques used to define and simulate digital filters for pilot devices are discussed. Noise measurements, system dynamics, and physical properties of the device are examined.

90 N74-31446
APPLICATION OF REDUNDANT DIGITAL COMPUTERS TO FLIGHT CONTROL SYSTEMS
Boeing Commercial Airplane Co., Seattle, Wash.
Schoenman, R.L. In AGARD Advan. in Control Systems
May 1974, 13p.

The use, operations, and failure modes of a redundant digital system for aircraft control are discussed. Emphasis is placed on the flight critical aspects such as automatic landing, command augmentation, and fly by wire control. The rationale for selecting digital flight control systems is explained. Specific application of digital flight control systems to the supersonic transport aircraft is analyzed. The system topics which are affected by the digital system are: (1) effect of cross-channel voting on reliability, (2) cross-channel voting mechanization, (3) input-output interface, and (4) the effect of actuator configuration. Block diagrams are included to show the interrelationships of the computer signals and components.

91 N74-31447
REALIZATION AND FLIGHT TESTS OF AN INTEGRATED DIGITAL FLIGHT CONTROL SYSTEM
Bodenseewerk Geraetetechnik G.m.b.H., Ueberlingen (West Germany)
Zach, R.K. In AGARD Advan. in Control Systems
May 1974, 20p, refs

The introduction of digital computers into modern aircraft control systems for the integration of all the functions in a complex automatic flight control system is discussed. In order to realize such practical systems economically, the functional requirements for the computer and interface were first derived by the analysis of the tasks and by the hybrid simulation of the functions, where the aircraft and actuators were simulated on an analog computer and the AFCS on a general purpose digital computer. Based on these requirements, a free programmable in-flight simulator was designed, built and flown in the test aircraft. This equipment is compatible with the laboratory hybrid simulation equipment. The in-flight simulator allows experiments of different control alws, and was used to check and prove the required control form for a special digital system developed for flight control. As is shown, this latter system fulfils all the functional requirements and consists of a small digital computer, an interface for signal conversion and a pilots control panel. All functions of a modern AFCS, such as stabilizer, automatic approach, automatic landing and other autopilot functions as well as preflight and inflight tests were integrated, by programming the semiconductor memory. The flight trials of this system in the test aircraft showed the satisfactory functioning of the system over the whole aircraft flight envelope. The good control characteristics were confirmed with the measured responses in flight.

92 N74-31450
DESIGN AND FLIGHT EXPERIENCE WITH A DIGITAL FLY-BY-WIRE CONTROL SYSTEM IN AN F-8 AIRPLANE
National Aeronautics and Space Administration Flight Research Center, Edwards, Calif.
Deets, D.A. and Szalai, K.J. In AGARD Advan. in Control Systems
May 1974, 10p, refs

A digital fly-by wire flight control system was designed, built and for the first time flown in an airplane. The system, which uses components from the Apollo guidance system, is installed in an F-8 airplane as the primary control system. A lunar module guidance computer is the central element in the three-exis, single channel, multimode, digital control system. A triplex electrical analog system which provides unaugmented control of the airplane is the only backup to the digital system. Flight results showed highly successful system operation,

92 N74-31450 (Contd.)

although the trim update rate was inadequate for precise trim changes, causing minor concern. The use of a digital system to implement conventional control laws proved to be practical for flight. Logic functions coded as an integral part of the control laws were found to be advantageous. Although software verification required extensive effort, confidence in the software was achieved.

93 N74-31451
DIGITAL FLY-BY-WIRE CONTROL SYSTEM WITH SELF-DIAGNOSING FAILURE DETECTION
Deutsche Forschungs- und Versuchsanstalt fuer Luft- und Raumfahrt, Brunswick (West Germany)
Onken, R., Joenck, H.P., Tacke, L. and Gottschlich, M. In AGARD Advan. in Control Systems
May 1974, 7p, refs

A solution is presented to the problem of achieving real fail-safe behaviour for fly-by-wire systems, no longer depending on the reliability of the monitor/voter device and the probability of the occurrence of dormant errors. This is accomplished by the use of stand-by redundancy in conjunction with self diagnosing failure detection which is independent of the control signal state. Each redundant unit is autonomous with respect to the failure detection, such that, depending on the inspection rate, perfect information about the reliability status of the system, including the failure detection itself, is available at any time. The feasibility of this approach is demonstrated by the fly-by-wire system which is installed and successfully flown in a HFB 320 jet aircraft.

94 N74-31452
B-52 CONTROL CONFIGURED VEHICLES PROGRAM
Air Force Flight Dynamics Lab., Wright Patterson AFB, Ohio.
Johannes, R.P. and Thompson, G.O. In AGARD Advan. in Control Systems
May 1974, 10p, refs Prepared in cooperation with Boeing Co.

A test program to evaluate the control configured vehicles (CCV) program is discussed. The purpose of the program is to validate achievable results of the CCV system concepts on large flexible aircraft, such as the B-52. The four concepts which are involved in the flight test are: (1) ride control, (2) flutter mode control, (3) maneuver load control, and (4) augmented stability. The potential benefits of the CCV concept and the results of the ride control system flight tests are analyzed.

95 A75-12825
FLY-BY-WIRE IS HERE
Exxon Air World, vol. 26, No.4, 1974, 95-99p

Fly-by-wire (FBW) is a form of flight control, by which the pilot is linked to the control surfaces through electrical, rather than mechanical, linkages. Flight tests have shown that FBW improves flight smoothness and aircraft control in turbulence. FBW is combined with the principle of controlled configured vehicle (CCV) in the American YF-16, the first airplane designed from the onset for FBW control. These features make possible a smaller, lighter, more economical fighter. An airborne computer is used to produce the most effective control movements to achieve piloting intentions. The pilot's control is through a side-stick controller. FBW control is being designed for helicopters in the USA and for other aircraft, such as the Concorde, in Europe.

96 A74-15953
THE LIGHT-WEIGHT HIGH-PERFORMANCE YF-17.
Geddes, J.P. Interavia, vol 28, Dec. 1973, 1315-1318p

The USAF outlined clear design objectives of the light-weight fighter, based on a 'day fighter', i.e., one that would operate in clear weather, usually under visual flight rules. The emphasis in performance is on transonic maneuverability. The aircraft is a twin-engined single seat model with a hybrid wing planform, set a mid-fuselage position. Distinguishing features are the large bubble cockpit, angled twin vertical tails set well forward of the large horizontal tail, and long leading edge extensions or strakes extending over the nostril engine inlets. The main design objective for the flight control system on the YF-17 was to provide a basic aerodynamic design that is stable and spin resistant without stability augmentation. The structure of the design is largely conventional.

97 A74-20120
DIGITAL ADAPTIVE FLIGHT CONTROLLER DEVELOPMENT
Kaufman, H and Berry, P. (Rensselaer Polytechnic Institute, Troy, N.Y.)
In: Conference on Decision and Control, 4th and Symposium on Adaptive Processes, 12th San Diego, Calif., December 5-7, 1973, Proceedings. (A74-20076) New York, Institute of Electrical and Electronics Engineers, Inc., 1973, 780-783p, 7 refs.
Grant No. NGR-33-018-183

The development of a digital adaptive flight control algorithm is described that combines a weighted least squares estimator with optimal linear regulator control logic designed to minimize a quadratic model following performance index. Very promising results for a typical fighter aircraft's trajectory over six distinct flight conditions are reported.

98 N74-30437
DESIGN METHODS FOR SPECIFYING HANDLING QUALITIES FOR CONTROL CONFIGURED VEHICLES
VOLUME 1: TECHNICAL DISCUSSION Technical Report, 15 Jan. - 15 Nov. 1973
McDonnell Aircraft Co., St. Louis, Mo.
Brulle, R.V. and Anderson, D.C.
15 Nov. 1973, 146p, refs.
(Contract F33615-73-C-3064)
(AD-780099: AFFDL-RD-73-142-Vol.1)

A method for predicting aircraft pilot ratings which is applicable to Control Configured Vehicles (CCV's) is developed based on aircraft performance and pilot workload. A discussion of this method of handling quality analysis, and a description of four random tracking pilot rating correlations developed using the method are presented in Volume 1 of the report. A literature survey classifying the most recent reports applicable to flying qualities is tabulated.

99 A74-13246
SOME STABILITY AND CONTROL ASPECTS OF AIRFRAME/PROPULSION SYSTEM INTERACTIONS ON THE YF-12 AIRPLANE
Berry, D.T. and Gilyard, G.B. (NASA, Flight Research Center, Handling Qualities Branch, Edwards, Calif.)
American Society of Mechanical Engineers, Winter Annual Meeting, Detroit, Mich., Nov. 11-15, 1973, Paper 73-WA/Aero-4. 7p.

Airframe/propulsion system interactions can strongly affect the stability and control of supersonic cruise aircraft. These interactions generate forces and moments similar in magnitude to those produced by the aerodynamic controls, and can cause significant changes in vehicle damping and static stability. This in turn can lead to large aircraft excursions of high pilot workload, or both. For optimum integration of an airframe and its jet propulsion system, these phenomena may have to be taken into account.

100 A74-11567
USE OF SIMULATORS IN THE DESIGN AND DEVELOPMENT OF FLIGHT CONTROL SYSTEMS
Gallagher, J.T. and Nelson, W. (Northrop Corp., Beverly Hills, Calif.).
Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, Los Angeles, Calif., Oct. 16-18, 1973, Paper 730933, 9p, 9 refs.

Recent advances in the design and development of motion simulators, visual display systems, artificial force producers, and computer capability have enhanced the effectiveness of ground-based simulators in the design process. At Northrop, a systematic improvement in simulator subsystems has resulted in the existence of the Northrop large amplitude three-axis flight simulator which has 6 degrees of freedom. The simulator is a significant tool in the design of flight control systems, particularly in today's environment where the aerospace industry is attempting to extend the performance envelopes of its products through the use of nonconventional configurations and radical flight control system concepts.

101 A74-15447
FEEDBACK CONTROL OF AN AIRPLANE WITH TIME VARYING GAIN
Murayama, T. (Defense Academy, Yokosuka, Japan) and Ozaki, T. Japan, Defense Academy, Memoirs, vol. 13, Sept. 1973, 357-372p, 5 refs.

The motion of an airplane with a large damping factor and stability following a disturbance may converge exponentially, but these injure the controllability. The motion of a conventional airplane following a disturbance is made oscillatory converging motion by compromising between stability and controllability. An airplane requiring high controllability, like the fighter, does not have good stability. Such an airplane usually has a stability augmentation system to obtain the necessary stability. The conventional stability augmentation system uses feedback controls of the rate of angle and displacement with fixed gains. The motion of an airplane with such a system following a disturbance is also an oscillatory converging motion. It is shown to be possible to make the motion of an airplane following a disturbance a nonoscillatory converging motion.

102 A74-34842
SURVIVABLE FLIGHT CONTROL SYSTEM FLY-BY-WIRE FLIGHT TESTING
Hunter, J.E. (USAF, Flight Dynamics Laboratory, Wright Patterson AFB, Ohio). In: Flight testing today - 1973; Proceedings of the Fourth National Symposium, Las Vagas, Nev., August 21-23, 1973. (A74-34837) California, Md., Society of Flight Test Engineers, 1973, 6p, 5 refs.

The Fly-by-Wire (FBW) portion of the Survivable Flight Control System (SFCS) Program is described. The program was aimed at developing a highly reliable flight control system, involving improvements in handling qualities, stability and performance, and weapon delivery accuracy. It is shown how the program's flight testing provided design criteria, reliability, cost and maintenance data, specification requirements, and the confidence level required for installation of an advanced flight control system in future aircraft. The quadruply redundant dispersed three-axis FBW primary flight control system allows the pilot to command aircraft motion, rather than the conventional control surface position. It is seen that the SFCS configuration will greatly reduce combat losses due to flight control damage.

103 A74-34838
AIR-TO-AIR TRACKING TECHNIQUES TO EVALUATE AIRCRAFT HANDLING QUALITIES
Schofield, B.L. and Franklin, D.L. (USAF Flight Test Center, Edwards AFB, Calif.). In: Flight testing today 1973; Proceedings of the Fourth National Symposium, Las Vegas, Nev., August 21-23, 1973. (A74-34837) California, Md., Society of Flight Test Engineers, 1973. 7p.

A flight study aimed at the development of handling qualities testing using tracking test techniques is described. Three air-to-air maneuvers were found to be useful in evaluating closed loop handling properties. These are the wind-up (increasing g) turn, the constant-angle-of-attack turn, and the reversal maneuver. All maneuvers were performed using a fixed gunsight, with the reticle only slightly depressed to avoid jet-wake encounters from the target aircraft. The tracking wind-up turn was found to be particularly useful for problem identification; it proved possible to quickly cover large ranges of angle of attack at a specific Mach number.

104 A73-37458
COMPATIBILITY OF MANEUVER LOAD CONTROL AND RELAXED STATIC STABILITY
Pasley, L.H., Rohling, W.J. and Wattman, W.J. (Boeing Co., Wichita, Kan.). American Institute of Aeronautics and Astronautics, Aircraft Design, Flight Test Operations Meeting, 5th, St Louis, Mo., Aug. 6-8, 1973, Paper 73-791, 10p 8 refs. Contract No. F33615-71-C-1181

The design of two classes of military aircraft, a bomber and a fighter, was used to investigate the compatibility of the relaxed-static-stability and maneuver-load-control concepts of advanced flight control technology in the achievement of significant flight performance improvements. The primary question to be answered was: do the two concepts operating simultaneously enhance or degrade each other and are the combined performance gains the sum of the gains of the individual concepts. The results of the investigation show that the two concepts are completely compatible. The performance benefits from each concept incorporated independently were essentially additive when both systems were incorporated simultaneously.

105 N73-31973
PREDICTING HEADING TASK FLYING QUALITIES WITH PAPER PILOT M.S. Thesis
Air Force Inst. of Tech., Wright-Patterson AFB, Ohio, School of Engineering
Taylor, C.R. Jun. 1973, 136p refs.
(AD-764695: GE/MA/73-1)

A mathematical model for predicting the pilot rating of a fighter aircraft in a precision heading task is described. The model includes the lateral-directional aircraft equations of motion, a stochastic gust model, a pilot model with four free pilot parameters, and a pilot rating expression that is a function of rms heading angle, rms yaw rate, and rms roll rate. The pilot gains and lead time constants are selected to minimize the pilot rating expression. The resulting minimum is used to compute a heading paper pilot rating. The heading paper pilot was computed for 32 flight conditions at different gust intensities for the F-5 and A-7 aircraft. Heading paper pilot ratings agree well with the actual ratings for the F-5, but are low for the A-7. In addition, there is good correlation between computed and actual rms heading angle, rms yaw rate, and rms slideslip.

106 N73-23881
AUTOMATION IN MANNED AEROSPACE SYSTEMS
Advisory Group for Aerospace Research and Development, Paris (France)
Mar. 1973, 322p refs in English and partly in French.
Presented at 24th Tech. Meeting of the Avionics Panel of AGARD.
Dayton, Ohio, 16-19 Oct. 1972.
(AGARD-CP-114)

Functional analyses of manned aerospace systems for the design of automatic avionic equipment are reported. Onboard computer capabilities to perform decision making functions, adaptice control, malfunction detection and compensation real-time control are considered.

107 N73-23905
MAN-MACHINE CONSIDERATIONS IN THE DEVELOPMENT OF A COCKPIT FOR AN ADVANCED TACTICAL FIGHTER
Boeing Co., Seattle, Wash.
Premselaar, S.J. and Frearson, D.E. (AFFDL) In AGARD Automation in Manned Aerospace Systems.
Mar. 1973, 20p.

No abstract available.

108 A73-22197
THE NATURE OF A FIGHTER AIRCRAFT
Sprey, P. Interavia, vol. 28, Feb. 1973, 145-147p

The characteristics of an air battle fighter are described. It is pointed out that a very high quality fighter can be built cheaply and easily if it is done correctly. However, despite its great utility in war no really superior fighter aircraft has been produced in the last 15 years by any nation. The basic traits that create a visual air battle fighter are considered, giving attention to lethality, maneuverability, stealth, range, battle persistence, visibility, presence (numbers), resilience, sortie rate, handling qualities, fire control system, and tactical doctrines.

109 A73-16907
COMBAT CONTROL VERSATILITY WITH CCV
Strahota, R.A. (USAF, Flight Dynamics Laboratory, Wright Patterson AFB, Ohio) and McGovern, D.R. (McDonnell Aircraft Co., St Louis, Mo.).
American Institute of Aeronautics and Astronautics, Aerospace Sciences Meeting, 11th Washington, D.C., Jan. 10-12, 1973, Paper 73-160, 8p.

The Control Configured Vehicles (CCV) F-4 Program is an R and D Program dedicated to control technology development to enhance fighter aircraft performance. Basic CCV concepts are examined, taking into account static stability compensation control, maneuver load control, precision flight path control and maneuver enhancement, control system design, and Canard technology. Advantages obtainable with the aid of CCV include smaller, lighter weight, and lower cost fighters.

110 A74-23091
AIRCRAFT SYMMETRIC FLIGHT OPTIMIZATION
Falco, M. (Grumman Aerospace Corp., Research Dept., Bethpage, N.Y.) and
Kelley, H.J. (Analytical Mechanics Associates, Inc., Jerico, N.Y.).
In: Control and dynamic systems (A74-23089) New York, Academic Press, Inc.,
1973, 89-129p 16 refs. Contracts No. AF29(600)-2671; No. AF 49(638)-1207;
No. NAS9-11532

Review of the development of gradient techniques and their application to aircraft optimal performance computations in the vertical plane of flight. Results obtained using the method of gradients are presented for attitude and throttle-control programs which extremize the fuel, range, and time performance indices subject to various trajectory and control constraints, including boundedness of engine throttle control. A penalty function treatment of state inequality constraints which generally appear in aircraft performance problems is outlined. Numerical results for maximum-range, minimum-fuel, and minimum-time climb paths for a hypothetical supersonic turbojet interceptor are presented and discussed. In addition, minimum-fuel climb paths subject to various levels of ground overpressure intensity constraint are indicated for a representative supersonic transport. A variant of the Gel'fand-Tsetlin 'method of ravies' is reviewed, and two possibilities for further development of continuous gradient processes are cited - namely, a projection version of conjugate gradients and a curvilinear search.

111 A73-20588
NONLINEAR PROGRAMMING IN DESIGN OF CONTROL SYSTEMS WITH SPECIFIED HANDLING QUALITIES
Schy, A.A. (NASA, Langley Research Center, Hampton, Va.). In: Conference on
Decision and Control and Symposium on Adaptive Processes, 11th New Orleans, La.,
December 13-15, 1972, Proceedings. (A73-20576) New York, Institute of Electrical
and Electronics Engineers, Inc., 1972, 272-279p.

A method is described for using nonlinear programming in the computer-aided design of aircraft control systems. It is assumed that the quality of such systems depends on many criteria. These criteria are included in the constraints vector, and the design proceeds through a sequence of nonlinear programming solutions in which the designer varies the specification of sets of requirements levels. The method is applied to design of a lateral stability augmentation system (SAS) for a fighter aircraft, in which the requirements vector is chosen from the official handling-qualities specifications. Results are shown for several simple SAS configurations designed to obtain desirable handling qualities over all design flight conditions with minimum feedback gains.

112 N73-16989
STABILITY AND CONTROL
Advisory Group for Aerospace Research and Development, Paris (France)
Nov. 1972, 305p refs Proceedings of the 40th Meeting of the Flight Mech. Panel
of AGARD, Braunschweig West Germany. 10-13 Apr. 1972 (AGARD-CP-119)

Summaries of papers presented at conferences concerning aircraft stability, control, maneuverability and design are reported.

113 N73-17008
POWERED CONTROLS, INFLUENCE ON STABILITY AND MANEUVERABILITY
Kissel, G.K. In AGARD Stability and Control
Nov. 1972, 13p

The influence is discussed of powered controls on the dynamic and static behavior of modern high performance aircraft. The possibilities of improving the stability and maneuverability by interconnections in the various axes are considered, and an example for a modern fighter type aircraft is demonstrated.

114 A73-37409
A PARAMETER OPTIMISATION TECHNIQUE APPLIED TO THE DESIGN OF FLIGHT CONTROL SYSTEMS
Gill, F.R., Watts, M.R. (Royal Aircraft Establishment, Farnborough, Hants., England).
In: Symposium on Optimisation in Aircraft Design, London, England November 15, 1972, Proceedings. (A73-37405) London, Royal Aeronautical Society, 1972. 9p.

A parameter optimization procedure and its application to design studies of numerous flight control modes and integrated systems are described. In this technique, control parameters are automatically and simultaneously selected to minimize a function chosen to represent all aspects of performance. One or two elements are minimized whilst constraining all others to be less than preselected values. Some problems are examined which have arisen in the application of the techniques to the design of complete systems or subsystems for practical evaluation in fighter-attack and transport aircraft. The example used for illustration is part of an elevator control system. It also illustrates the complexity of a relatively simple problem. Elements of the hybrid computer program used in parameter optimizations are described.

115 A72-45386
NEW CONTROLS TO SHAPE FUTURE AIRCRAFT
Yaffee, M.L. Aviation Week and Space Technology, vol. 97, Oct. 16, 1972, 46-50p

Studies and development programs on control-configured vehicles (CCV) are expected to result in aircraft with greatly improved performance. The CCV concept involves application of advanced flight control technology, such as the static stability compensation system, to aircraft while they are still in the design stage. These new control systems can replace and enhance to a significant degree many of the control functions now performed by pilots and conventional control surfaces. They also will enable aircraft to make maneuvers such as side steps that could not be done before. Fighter and bomber aircraft were studied, and an advanced development program was established that is structured to generate the flight control technology most appropriate to each class.

116 A73-16662
COMBAT CAPABILITIES AND VERSATILITY THROUGH CCV
Bennett, D.H. (McDonnell Aircraft Co., St Louis, Mo.) and Johannes, R.P. (USAF, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio).
Society of Automotive Engineers, National Aerospace Engineering and Manufacturing Meeting, San Diego, Calif., Oct. 2-5, 1972, Paper 720854, 9p

Advanced design studies indicate that use of control configured vehicle (CCV) concepts can provide improvements in combat capability and versatility. These benefits will be evidenced by improved performance and survivability, as well as by new maneuvering capabilities not avialable to pilots of current aircraft. The fly-by-wire (FBW) techniques, utilized to enable CCV, also provide the potential for improved flying qualities. The end result of applying these concepts in the preliminary design stages can be a lighter weight fighter aircraft to do a given job better.

117 N73-23002
FEASIBILITY STUDY FOR AN ADVANCED DIGITAL FLIGHT CONTROL SYSTEM (DIGIFLIC). VOLUME 1: SUMMARY ANALYSIS, AND SYSTEM STUDIES, VOLUME 2: SOFTWARE, SPECIFCATION, SIMULATION STUDIES, AND APPENDICES Final Report, Sep. 1971 - Aug. 1972.
Sutton, M.L., Hasson, W.J. and Soderlund, G.M.
Oct. 1972, 490p refs
(Contract N62269-72-C-0142)
(AD-757271; ADR-773-Vol-1-2)

The digital flight control system (DIGIFLIC) program is an advanced development program of which the principle objective was to study the feasibility of advanced flight control using a digital processor as the main computational element. The studies and analyses conducted during this program resulted in the determination of a set of basic system requirements which could be implemented using present day technology. Investigation of future technology showed that significant advances can be expected which will reduce the size, weight and power required for such a flight control system. The results of these studies are contained in two volumes. Volume 1 contains a detailed summary of the objectives and results, analytical studies and system studies. Volume 2 contains the software studies, system specification, simulation studies and appendices.

118 A73-22177
SURVIVABLE FLIGHT CONTROL SYSTEM
Garrison, C.P. (McDonnell Douglas Corp., St. Louis, Mo)
(Society of Experimental Test Pilots, Symposium, 16th, Beverly Hills, Calif., Sept. 28-30, 1972)
Society of Experimental Test Pilots, Technical Review, vol. 11, No.2, 1973, 1-19p

Review of the design and flight test philosophy, present status and future trends of the projected survivable flight control system for fighter aircraft. A description of the test vehicle is followed by a discussion of the results of the flight test program. Observations regarding the future of redundant, full-authority, motion-feedback control systems conclude the review.

119 A72-45349
CONTROL REQUIREMENTS FOR CONTROL CONFIGURED VEHICLES
Watson, J.H. (General Dynamics Corp., Convair Aerospace Div., Fort Worth, Tex.)
In: Atmospheric Flight Mechanics Conference, 2nd, Palo Alto and Moffett Field, Calif., September 11-13, 1972, Informal Papers. (A72-45326) Moffett Field Calif., NASA Ames Research Center, 1972, 33.1-33.9p 6 refs.
Research supported by the General Dynamics Corp.

Of the emerging new technologies, the control configured vehicle (CCV) concept of reduced static stability holds considerable promise in improving performance and maneuverability and in reducing weight while retaining excellent handling qualities. This paper defines additional pitch control power requirements for CCV airplanes; contains design charts for small fighter airplanes during power approach; and includes the effects of static margin, discrete gusts, lift coefficient, zero-lift pitching moment, pitch inertia, C sub m-C sub L linearity, and actuator rate limits, time constants and nonlinearities. Proper shaping of the pitching moment curve, and proper design of the automatic flight control system, during preliminary airplane design stages minimizes pitch control power requirements.

120 A72-39129
MANEUVER LOAD CONTROL AND RELAXED STATIC STABILITY APPLIED TO A CONTEMPORARY FIGHTER AIRCRAFT
Anderson, D.C., Berger, R.L. and Hess, J.R. (McDonnell Aircraft Co., St Louis Mo.)
American Institute of Aeronautics and Astronautics, Guidance and Control Conference, Stanford, Calif.
Aug. 14-16, 1972, Paper 72-870, 13p
Contract No. F33615-71-C-1234

Analytical investigation of the possibility to improve the maneuvering performance of fighter aircraft through application of such aircraft design concepts as those of maneuver load control (MLC) and relaxed static stability (RSS). The analysis results show that significant performance benefits can be realized through judicious application of these design concepts. Relaxing static stability and using combinations of horizontal canards and high-lift control surfaces lead to improvements in such characteristics as specific excess power and lift-limited load factor, while the use of optimal control techniques in determining the control system compensating network parameters can ensure the desired system performance and stability. These control characteristics are achievable with conventional control implementation means such as the fly-by-wire control system. The MLC and RSS design concepts are shown to be compatible and mutually complementary.

121 A72-39090
ADVANCED FIGHTER CONTROLS FLIGHT SIMULATOR FOR ALL-SYSTEMS COMPATIBILITY TESTING
Rayhawk, S., Rolston, D.R. and Barnes, B.B. (McDonnell Aircraft Co., St Louis, Mo.)
American Institute of Aeronautics and Astronautics, Guidance and Control Conference, Stanford, Calif., Aug. 14-16, 1972, Paper 72-837, 11p.

No abstract available.

122 A72-35564
ANALYSIS OF PILOTED WEAPON DELIVERY
Rankine, R., Hoyde, R., Minnich, T and Morton, D. (USAF, Institute of Technology, Wright Patterson AFB, Ohio).
In: NAECON '72 Proceedings of the National Aerospace Electronics Conference, Dayton, Ohio, May 15-17, 1972. (A72-35551) New York, Institute of Electrical and Electronics Engineers, Inc., 1972, 126-135p, 20 refs.

Description of a model of the pilot-aircraft system which can relate the pilot tracking performance attainable with specific aircraft dynamics to the overall accuracy of tactical weapon delivery is required in order to realistically determine essential flight control system dynamic performance characteristics. The approach taken is to derive an expression for projectile impact error in terms of errors in the task variables which are directly under the pilot's control. Mathematical representations of the aircraft and control system dynamics, the turbulence environment, and the human pilot are used to estimate the tracking error contribution. The resulting weapon delivery model provides a mission-oriented basis for comparing the effectiveness of display, computation, and control system designs as illustrated by an F-4C example.

123 A72-35561
MULTIMODE FLIGHT CONTROL FOR PRECISION WEAPON DELIVERY
Quinlivan, R. and Tye, G. (General Electric Co., Aircraft Equipment Div., Bingham, N.Y.) In: NAECON '72 Proceedings of the National Aerospace Electronics Conference, Dayton, Ohio.
May 15-17, 1972. (A72-35551) New York, Institute of Electrical and Electronics Engineers, Inc., 1972, 103-109p
Contracts No. F33615-70-C-1172; No. F33615-71-C-1485

Significant benefits can accrue from simple changes in control augmentation associated with the precise delivery of different types of unguided weapons, rather than designing a single augmentation system which is a compromise among all the various modes of weapon delivery. Realization of the benefits, however, requires a direct display of the particular controlled variable so that it may be observed with respect to the appropriate reference. Results from man-in-the-loop simulation of various control and display configurations are presented. Flight control requirements for air-to-ground gunnery are shown to be significantly different from those most appropriate for air-to-air gunnery from fixed-gun fighter aircraft.

124 N73-32978
FLIGHT CONTROL SYSTEMS: REQUIREMENTS AND DESIGN PROBLEMS FROM THE FLIGHT MECHANICS VIEWPOINT (FORDERUNGEN AN FLUGREGELANLAGEN UND AUSLEGUNGSPROBLEME UNTER BESONDERER BERUECKSICHTIGUNG DER FLUGMECHANIK)
Deutsche Gesellschaft fuer Luft- und Raumfahrt, Cologne (West Germany)
Mar. 1972, 209p refs in German; English summary Proc. of the DGLR Flight Characteristics and Flight Control Panels Meeting. Immenstaad, West Ger. 28-29 Oct. 1971 (DLR-MITT-72-05)

The application of artificial stabilizing devices to particular cases of instability in flight control is discussed. Based on a unified point of view, basically possible feedback control concepts were derived for aircraft with variable stability. The optimization of a control and damping system for fighter aircraft is described. The specification of a thrust control system for the Airbus A300B is presented. The role of an airborne computer in digital flight control systems is detailed. The DO-31 V/STOL aircraft's control system for vertical velocity regulation is described. The flight control system of the VAK 191 B VTOL fighter aircraft is presented. The design optimization of the flight control systems for light helicopters is exemplified by the BO-105 helicopter. Some effects of artificial stability are reviewed.

125 N73-32980
DESIGN OF A MODERN FIGHTER AIRCRAFT CONTROL SYSTEM USING QUADRATIC COST FUNCTIONS (AUSLEGUNG EINES REGELSTSTEMS FUER MODERNE KAMPFFLUGZEUGE MIT HILFE QUADRATISCHER KOSTENFUNKTIONEN)
Schaenzer, G and Stadler, R. In DGLR Flight Control Systems Requirements and Design Probl from the Flight Mech. Viewpoint.
Mar. 1972, 17-36p refs in German

The optimization of a control and damping system for fighter aircraft is discussed Essential specifications, such as gust and flight control behavior, and stability, can be described exactly by a single quadratic integral quality criterium (cost function). It is shown that the controller, optimized for minimal costs, gives an especially favorable performance related to flight control, disturbance, stability and parameter sensitivity. The investigation of parameter sensitivity produced indications for technical simplification of the control system structure.

126 N73-32986
EFFECT OF ARTIFICIAL STABILITY ON AIRCRAFT PERFORMANCES (EINFLUSS DER KUENSTLICHEN STABILITAET AUF DIE FLUGLEISTUNGEN)
Messerschmitt-Boelkow-Blohm G.m.b.H., Ottobrunn (West Germany)
Reich, D. In DGLR Flight Control Systems: Requirements and Design Probl. from the Flight Mech. Viewpoint.
Mar. 1972, 171-186p in German

Based on the control configured vehicle (CCV) concept, i.e. taking account of the flight control during the design phase, the effect of an artificial longitudinal stability on the performance of aircraft was investigated. In consequent application of the CCV concept, in the most favorable cases a decrease of about 15% in takeoff weight (for the same radius of action) or an increase of 11% in radius of action (for the same takeoff weight) can be achieved. For a fighter aircraft, it is shown that the advantages of an artificial longitudinal stability are obtained for high lift coefficients and for plane wing-body drag polars.

127 N72-18013
LONGITUDINAL STABILITY AND CONTROL DERIVATIVES OF A JET FIGHTER AIRPLANE EXTRACTED FROM FLIGHT TEST DATA BY UTILIZING MAXIMUM LIKELIHOOD ESTIMATION
National Aeronautics and Space Administration, Langley Research Center, Langley Station, Va.
Steinmetz, G.G., Parrish, R.V. and Bowles, R.L. Washington
Mar. 1972, 44p, refs. (NASA-TN-D-6532; L-7882)

A method of parameter extraction for stability and control derivatives of aircraft from flight test data, implementing maximum likelihood estimation, was developed and successfully applied to actual longitudinal flight test data from a modern sophisticated jet fighter. The results of this application establish the merits of the estimation technique and its computer implementation (allowing full analyst interaction with the program) as well as provide data for the validation of a portion of the differential maneuvering simulator (DMS). The results are presented for all flight test runs in tabular form and as time history comparisons between the estimated states and the actual flight test data. Comparisons between extracted and manufacturer's values for five major derivatives are presented and reveal good agreement for these principal derivatives with one exception. This particular derivative is extensively investigated by utilizing the interactive capabilities of the computer program. The results of this investigation verify the numbers extracted by maximum likelihood estimation.

128 N72-18012
INVESTIGATION OF AN AUTOMATIC SPIN PREVENTION SYSTEM FOR FIGHTER AIRPLANES
National Aeronautics and Space Administration. Langley Research Center, Langley Station, Va.
Gilbert, W.P. and Libbey, C.E. Washington
Mar. 1972, 49p refs.
(NASA-TN-D-6670; L-8112)

An investigation was conducted to evaluate the effectiveness of an automatic spin-prevention system for current fighter airplanes as a first step in determining the feasibility of such a system. The concept makes use of the components of the conventional flight-control system with the addition of control logic to monitor angle of attack, yaw rate, and normal acceleration. Analytical techniques were used to study the system concept applied to three representative fighter

128 N72-18012 (Contd.)

configurations, and model flight tests were employed to evaluate a protective system on a representative figher configuration. Emphasis was placed on the development of the control logic required. A discussion of possible implementations of the system concept is presented. Results of the investigation indicated that a relatively simple system (with full control authority) was effective in preventing the developed spins of the fighter configurations considered and that the system design is dependent on the stall and spin characteristics of the particular airplane.

129 A73-30353
GENERAL PRINCIPLES OF DESIGNING CONTROL SYSTEMS (Obshchie printsipy proektirovaniia sistem upravieniia).
Chembrovskii, O.A., Topcheev, Iu. I. and Samoilovich, G.V. Moscow, Izdatel'stvo Mashinostroenie, 1972, 415p, 215 refs. in Russian.

General methods of designing aircraft, rocket and spacecraft control systems are discussed with particular reference to methods based on statistical estimates of the performance characteristics. Ground and onboard control systems and methods of synthesizing them are examined. The effectiveness of the control systems under various operating conditions is assessed. Formulas and graphs suitable for use in preliminary design are presented.

130 A72-16657
A SIMPLIFIED CRITERION FOR OPTIMIZATION AND EVALUTATION OF COMBAT AIRCRAFT LATERAL AIMING PERFORMANCE
Bailey, D.G. (Honeywell, Inc., Government and Aeronautical Products Div., St Paul, Minn.) and Mobarg, M. (Saab-Scania AB, Goteborg, Sweden).
In: Symposium on Test and Evaluation of Automatic Control Systems, Saint May's College of Maryland, Saint Mary's City, Md.,
August31 - September 2, 1971, Technical Papers. (A72-16652)
California, Md., Society of Flight Test Engineers, 1971. 37p.

Suggestion of a criterion for optimization and evaluation of combat aircraft lateral aiming performance. The criterion applies to lateral bullet stream response to pilot roll commands, and is intended to provide a reference for objective evaluation of the ability of a particular system to hit a target with bullets from a body-mounted gun. It was found that at positive load factors, bullet stream lateral rate response to small bank angles should be fast and stable, with no rate reverses. Optimization of the lateral rate response can produce violations of existing handling quality requirements, i.e., sideslip transients during roll maneuvers.

131 A71-44109
A FEASIBILITY STUDY OF ACTIVE WING/STORE FLUTTER CONTROL
Triplett, W.E. (McDonnell Aircraft Co., St Louis, Mo).
In: Joint Automatic Control Conference, 12th Washington University, St. Louis, Mo., August 11-13, 1971, Preprints of Technical Papers. (A71-44076)
New York, Institute of Electrical and Electronics Engineers, Inc., 1971, 624-632p, 12 refs.

Analytical investigations of active feedback flutter control for fighter type aircraft, specifically with respect to wing/store flutter control, show promise of significant benefits for both contemporary and future aircraft. The F-4 Phantom aircraft with an external store is idealized for a flutter critical configuration. Computer programs, based on both frequency and time domains, are used with conventional control system design techniques to generate feedback compensation for active control of flutter for this configuration. Results of linear analyses indicate the possibility of expanding the permissible flight envelope by 150 knots using the existing aileron control surfaces and establish preliminary requirements for control system hardware.

132 A71-34016
LONGITUDINAL ANALYSIS OF TWO CCV DESIGN CONCEPTS
Kujawski, B.T., Jenkins, J.E. and Eckholdt, D.C. (USAF, Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio)
American Institute of Aeronautics and Astronautics, Aircraft Design and Operations Meeting, 3rd Seattle, Wash., July 12-14, 1971, Paper 71-786, 11p, 8 refs.

Results are presented of an investigation into the longitudinal control requirements due to simultaneous application of relaxed static stability (RSS) and maneuver load control (MLC). Two Control Configured Vehicle (CCV) design concepts - i.e., concepts involving the application of advanced flight control techniques to permit the relaxation of certain traditional design constraints - are considered. A previously described dynamic response criterion is applied first to a fighter-type aircraft, with the exception that the duration of the maneuver is selected based on the short period response requirements for acceptable handling qualities. The approach to MLC was modified to include directly the effects of induced drag. This provided improved capability to investigate the tradeoffs between wing-root-bending alleviation, drag, and longitudinal trim change. As a result of the new approach, improved solutions were found for a bomber configuration previously investigated.

133 N72-26077
A HUMAN MODEL WHICH OPTIMIZES PURSUIT TRACKING Ph.D Thesis.
Louisiana State Univ., Baton Rouge
Caluda, M.J. 1971, 144p

The feasibility of using an adaptive linear mathematical model to represent a human operator subjected to the task of controlling an attacking fighter aircraft was investigated. The ability of the model to perform pursuit tracking tasks subject to random evader tactics was analyzed by the implementation of the model into a six degree of freedom digital fire control simulation. For the model to approach reality in every flight regime, an adaptive procedure was incorporated into the simulation to adjust the variable gain and lead time parameters of the human model. As a means of evaluating the simulated performance of the human operator when performing this task, the performance data of the attacking aircraft was subjected to a number of spectral analysis operations. These spectral operations compared the frequency content of the data obtained from the simulation to actual data obtained from combat flight maneuvers. For both sets of data the evaders performed the same identical tactics.

134 N71-27354
STABILITY AND CONTROLLABILITY OF SUPERSONIC AIRCRAFT
Air Force Systems Command, Wright-Patterson AFB, Ohio, Foreign Technology Div.
Lutskii, V et al. 4Dec, 1970, 10p. Translation into English from Aviatsiya i Kosmonavtika (Moscow), No.12, 1969 12-22p
(AD-721027: FTD-HC-23-598-70)

In distinction from the subsonic aircraft in which the system of longitudinal control was quite simple and the favorable conditions of controllability fully assured a rigid kinematic coupling of the control stick with the elevator, the control system on supersonic machines is more complex; it includes hydraulic control boosters, automatic loading units, trimmer effect mechanisms and elements increasing the operational reliability. In modern fighters, an adequate effectiveness of the horizontal tail empennage at supersonic flight modes is achieved only in the presence, in the control system, of a fully rotatable control surface, i.e. of a controlled stabilizer. On the supersonic aircraft having limited maneuverability, longitudinal controllability is provided by the elevator and by a stabilizer which is adjustable during flight.

135 N71-25846
A COMPARISON OF PILOT PERFORMANCE USING A CENTER STICK vs SIDE ARM CONTROL CONFIGURATION. Technical Report, May - Oct. 1968.
General Precision. Inc., Birmingham, N.Y. Link Group
Geiselhart, R, Kemmerling, P., Cronburg, J.E. and Thorburn, D.E. Wright-Patterson AFB, Ohio, AFSC Nov. 1970, 54p refs.
(Contract F33615-68-C-1097)
(AD-720846; ASD-TR-70-39)

Six Air Force pilots having current flying status flew a series of forty-minute missions to compare pilot performance with the conventional center stick, dual side stick, and single side stick configurations. An F-111 flight simulator with three degrees-of-motion was employed as the test-bed for the experiment. The missions, which included climbout, a terrain following portion, two banking turns, and five instrument Landing System (ILS) approaches, were designed to test the feasibility of side stick controllers under low-altitude, high-speed conditions. Course steering deviation, airspeed deviation, pitch deviation, and ILS evaluation scores were obtained using the computer to compare pilot performance using the three stick configuration. From the evaluation of the performance data and opinion questionnaires filled out by the pilots, it was concluded that side stick controllers are feasible for use in a relatively high-speed aircraft flying a low-altitude, high-speed mission, and that dual side sticks are preferable to single side sticks. Recommendations were made for further studies in several areas.

136 A70-42711
HIGHER-ORDER CONTROL SYSTEM DYNAMICS AND LONGITUDINAL HANDLING QUALITIES
DiFranco, D.A. (Cornell Aeronautical Laboratory, Inc., Buffalo, N.Y.)
(American Institute of Aeronautics and Astronautics, Aircraft Design and Operations Meeting, Los Angeles, Calif., July 14-16, 1969, Paper 69-768)
Journal of Aircraft, vol. 7, Sept.-Oct. 1970, 457-464p, 7 refs.
Contract No. AF 33(615)-3294

No abstract available.

137 A70-35837
DEVELOPMENT OF A FLYING QUALITIES CRITERION FOR THE DESIGN OF FIGHTER FLIGHT CONTROL SYSTEMS
Neal, T.P. and Smith, R.E. (Cornell Aeronautical Laboratory, Inc., Buffalo, N.Y.)
American Institute of Aeronautics and Astronautics, Aircraft Design and Operations Meeting, 2nd, Los Angeles, Calif., July 20-22, 1970, Paper 70-927.
13p, 10 refs
Contract No. AF 33(615)-69-C-1664

It is readily apparent that current longitudinal flying qualities criteria do not adequately account for the effects of dynamic modes introduced by today's complex flight control systems (FCS). To remedy this situation, a combined analytical and experimental investigation was recently conducted, using the USAF/CAL variable -stability T-33 airplane. Based on an extensive pilot-in-the loop analysis of the experimental results, a design criterion was developed which is shown to be applicable to a wide range of short-period and FCS dynamics. A simplified version is also presented to provide the designer with preliminary estimates of flying qualities.

138 A70-23021
FIGHTER FLIGHT CONTROL SYSTEM DESING CONSIDERATIONS
Nardi, L.U. (North American Rockwell Corp., Los Angeles, Calif.).
American Institute of Aeronautics and Astronautics, Fighter Aircraft Conference, St Louis, Mar. 5-7, 1970, Paper 70-515, 11p.

A preliminary design effort is reviewed to present the system requirements, configuration characteristics, and technology applications which are significant in fighter flight control system design. Criteria to provide maximum combat effectiveness, safety, and survivability in the design without excessive program cost or risk are included. The impact of studies in the areas of stability and control, precision flying, control actuation, hydraulic power, safety, redundancy, and emergency modes on the selection of specific flight control system design features is highlighted, and the resultant preliminary design is summarized. It is concluded that effective, safe, and survivable control of the fighter aircraft can be accomplished within the current technology and that attention to vehicle design can minimize flight control system cost and complexity.

139 N70-40701
PRELIMINARY DESIGN ASPECTS OF MILITARY AIRCRAFT
Advisory Group for Aerospace Research and Development, Paris (France)
Mar. 1970, 303p, refs Presented at 35th Meeting of the Flight Mech. Panel of AGARD, The Hague, 2 - 5 Sept. 1969
(AGARD-CP-62)

The aspects discussed included project design, aerodynamics power plants, structures, airframe systems, and operational systems and requirements.

140 N70-40708
FUTURE ADVANCES IN THE AERODYNAMICS OF MILITARY STRIKE AIRCRAFT
Aeronautical Systems Div. Wright-Patterson AFB, Ohio
Klepinger, R.H., Carlson, J.W. and Stout, W.M. In AGARD Prelim. Design Aspects of Mil. Aircraft Mar. 1970, 18p, refs (See N70-40701)

The primary mission requirements of an air superiority fighter are reviewed, and the factors which affect performance and maneuverability are discussed. The aerodynamic features which have a strong influence on fighter capability are indicated. The effect of the rapid development of numerical solution techniques, using the digital computer, on aerodynamic design methods is noted. The current trend toward configurations with minimum basic aerodynamic stability and extensive stability augmentation is discussed. The need for improved aerodynamic stability is emphasized, and some of the current flight problems of supersonic fighter aircraft are described. It is shown that stability augmentation can cause adverse effects in some flight regimes. The analyses and test programs that are essential before an aerodynamic design is committed to production are summarized.

141 N70-40716
ADVANCED STUDIES IN THE FIELD OF FLIGHT CONTROLS (ETUDES AVANCEES DANS LE DOMAINE DES COMMANDES DE VOL)
Service Technique de l'Air, Paris (France)
In AGARD Prelim. Design Aspects of Mil. Aircraft May 1970, 35p In French
Prepared in cooperation with sud-Aviation, Paris (See N70-40701)

Problems met in the design of modern combat aircraft are discussed, including the increase of the power necessary for activating the control surfaces, variations of stability and controllability characteristics, the introduction of severe perturbations linked, for example, to the Mach number, structural deformations, and safety problems. Some possible solutions to the problems are examined. The system of flight control of the civil supersonic transport aircraft Concorde is then investigated with reference to performance objectives and objectives of reliability, in the sense of navigability and operational utilization. Application of these objectives to the general design of the system and to its technology is discussed. An electrical system of transmitting the piloting orders, which integrates a plurality of automatic navigation aids, is utilized, which is derived from advanced military aircraft development.

142 N70-40717
ADVANCES IN AIRCRAFT CONTROL SYSTEMS WITH PARTICULAR REFERENCE TO COMBAT AIRCRAFT
Royal Aircraft Establishment. Farnborough (England), Avionics Dept.
Howell, G.C. In AGARD Prelim. Design Aspects of Mil. Aircraft.
Mar. 1970 15p, refs (See N70-40701)

A review of current flight control system design for combat aircraft is given, highlighting the reliance placed on forms of electrical signalling of the flying control surfaces and the increasing use of feedback control techniques to achieve satisfactory handling qualities. In all current systems, however, a mechanical backup system is retained. A description of a possible electrical signalling system design is given, including maneuver demand control characteristics, and some of its advantages are discussed. The conclusion is reached that, although some experience is being gained in service of forms of electrical signalling, aircraft designers have not yet the confidence to eliminate mechanical reversion systems; these often compromise the primary electrical signalling system performance. Recent system developments should lead to the abandoning of these mechanical reversion systems in future project designs and the full benefits of feedback control can then be obtained. These include the optimization of the overall airframe, taking advantage of feedback control, and new cockpit layouts, taking advantage of the use of small side controllers.

143 A69-35655
HIGHER-ORDER CONTROL SYSTEM DYNAMICS AND LONGITUDINAL HANDLING QUALITIES
DiFranco, D.A. (Cornell Aeronautical Laboratory, Inc., Flight Research Dept., Buffalo, N.Y.)
American Institute of Aeronautics and Astronautics, Aircraft Design and Operations Meeting, Los Angeles, Calif., July 14-16, 1969, Paper 69-768. 12p, 7 refs.
Contract No. AF 33(615)-3294

Evaluation of an experimental investigation of the effects of higher-order control system dynamics on the longitudinal handling qualities of a figher aircraft. This research was undertaken using the USAF/Cornell Aeronautical Laboratory variable-stability T-33 aircraft as an in-flight simulator. Different higher-order responses were simulated by altering the elevator feel system, elevator actuator, and aircraft short-period characteristics. Essentially the same configurations were evaluated by two pilots using a revised pilot rating scale. One pilot also rated the configurations for their PIO (pilot-induced oscillations) tendencies. Comments and ratings were related to a response delay parameter. Many of the higher-order control systems investigated produced pronounced PIO tendencies in flight, and some were considered unflyable with certain higher-order characteristics. A comparison of fixed-base and in-flight evaluations indicated that configurations with significant PIO tendencies were rated poorer in flight and configurations with little or no PIO tendencies were rated better in flight.

144 A69-33319
FLIGHT MECHANICS: AIRCRAFT AND MISSILE PERFORMANCE (LA MECANIQUE DU VOL: PERFORMANCES DES AVIONS ET DES ENGINS) (2nd Edition)
George, L., Vernet, J.F., Wanner, J.C.
Paris, Dunod Editeur, 1969, 508p 9 refs. in French.

The work is intended for students and research engineers, particularly those concerned with optimization methods. After formulating the problem, attention is given to a consideration of mass forces, propulsion, aerodynamics, and transonic and supersonic aerodynamic forces. Aspects of altitude and speed are also considered. The equations of flight, principles of control, and the calculation of performances are discussed, as well as aspects of power and thrust. The characteristics of level flight and tunning for propeller aircraft and jet aircraft, are studied. Motorless flight is also examined. Longitudinal accelerations, climbing at practically constant speed, and optimal flight paths are discussed. Problems connected with takeoff and landing, and with attainable range and antonomy are examined. Examples of optimization problems of transport aircraft, and elementary concepts of stability and maneuverability are given, and phenomena which limit performance are studied. Four appendices deal with a graphical method of treating the lift equation propulsion by propeller, reentry and flight of a hypersonic glider, and the influence of atmospheric movements on aircraft performance.

145 A68-19713
THE EFFECT OF FLYING QUALITIES REQUIREMENTS ON THE DESIGN OF GENERAL AVIATION AIRCRAFT IN THE 1980'S
Larrabee, E.E. and Tymczyszyn, J.P. (Massachusetts Institute of Technology, Cambridge, Mass.)
American Institute of Aeronautics and Astronautics, Aircraft Design for 1980 Operations Meeting, Washington, D.C., Feb. 12-14, 1968.
Paper 68-189, 8p, 10 refs

Review of the problem of specifying aircraft flying qualities to determine the applicability of existing requirements to aircraft design. Classification of flight situations into three categories, "unattended behavior," "limiting performance," and "precision flying" is suggested as a way of defining requirements for stability, control and the man-machine relation. Parallel flight-test and simulator programs are recommended to test new requirements so classified. Specific problem areas are discussed.

AUTHOR INDEX

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14. Abstract

Recent developments in data processing are establishing the viability of high-integrity, high-authority full-time electrical flight control systems, which in turn offer a range of new possibilities in the design of the control system and of the complete aircraft. The use of digital processors now allows the control system characteristics to be varied during or between flights to match particular operational needs. This concept of Task-Oriented Control Systems is the subject of this Lecture Series, which aims to present information on the benefits, problems, design and engineering aspects of these new developments, commencing with a state-of-the-art review of modern flight control theory and practice. The contributions are based on the practical experience of the authors and their organisations in several nations. This Lecture Series was recommended by the Guidance and Control Panel of AGARD and is implemented under the Consultant and Exchange Programme. A bibliography of 145 items is included in the publication.

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